RURAL FACILITY ELECTRIC POWER QUALITY ENHANCEMENT

Final Report

Report No. AK-RD-91-11

STATEWIDE DOT & PF RESEARCH

INE88.13.2

RURAL FACILITY ELECTRIC

POWER QUALITY ENHANCEMENT

FINAL REPORT

by

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May 1991

Prepared for:

STATE OF ALASKA
DEPARTMENT OF TRANSPORTATION AND PUBLIC FACILITIES
STATEWIDE RESEARCH
2301 Peger Road
Fairbanks, Alaska 99709-5316

Production Cost: $17.20

ABSTRACT

Electric power disturbances are known to be more prevalent in small, isolated power systems than in larger interconnected grids which service most of the United States. This fact has given rise to a growing concern about the relative merits of different types of power conditioning equipment and their effectiveness in protecting sensitive electronics and essential loads in rural Alaska.

A study has been conducted which compares isolation transformers, voltage regulators, power conditioners, uninterruptible power supplies and indoor computer surge suppressors in their ability to suppress the various disturbances which have been measured in several Alaskan communities. These include voltage sags and surges, impulses, blackouts, frequency variations and long-term voltage abnormalities. In addition, the devices were also subjected to fast, high-magnitude impulses such as might be expected in the event of a lightning strike to or near utility distribution equipment.

The solutions for power line problems will vary for different load applications and for different rural electrical environments. The information presented in this report should prove to be valuable in making the analysis.

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ACKNOWLEDGMENTS

This research was made possible by financial support provided by the Department of Transportation and Public Facilities (DOT&PF) Research Section. The authors are indebted to many people who assisted both directly and indirectly with this project.

Special thanks for support go to TESCO Lighting and Design Center, Far North Atari, MicroAge, and Today's Business Computer Center of Fairbanks by providing the computer surge suppressors which were tested during the course of the project. Thanks also to Stan Gregory of Consulting Engineers for providing the KeyTek impulse generator as well as technical support.

CHAPTER 1

ELECTRICAL DISTURBANCES IN POWER SYSTEMS

Introduction

Poor electric power quality is often the cause of malfunctions and failure of equipment designed to operate from the utility AC power supply. This is especially true for smaller, isolated systems such as those which serve rural communities as well as emergency/standby diesel engine-generator sets.

Although the blame for power line disturbances is commonly placed on the utility, probably the greatest number of short-term voltage disturbances seen by electronic equipment are caused by the switching on and off of local customer loads. No power system is free from electrical transients and in most cases the power utility may have little, if any, control over the transient environment within localized areas of the distribution network.

In a large, interconnected power system switching and lightning constitute the two primary causes of high voltage transients on the AC power line. The incidence of lightning-induced disturbances is proportional to the thunderstorm-day probability level for a particular area which varies considerably throughout the United States. For all of Alaska this *keraunic* level is relatively low (Fig. 1), although lightning does occur during the summer months throughout much of the state. A keraunic level of 5 suggests that thunder can be heard on an average of five days a year in a particular location.

In a small, isolated power system, load switching and lightning can induce fast, high-voltage surges by the same mechanisms which operate on larger systems. A *fast* transient refers to the rate-of-rise of the leading edge of a transient impulse, or spike, and not to the propagation velocity in the transmission conductors. In addition to the presence of short-duration transients, rural power systems can occasionally be subjected to severe low voltage/low frequency conditions which are uncommon in large, interconnected power networks. These events may be the most devastating to the operation of essential loads in rural Alaska.

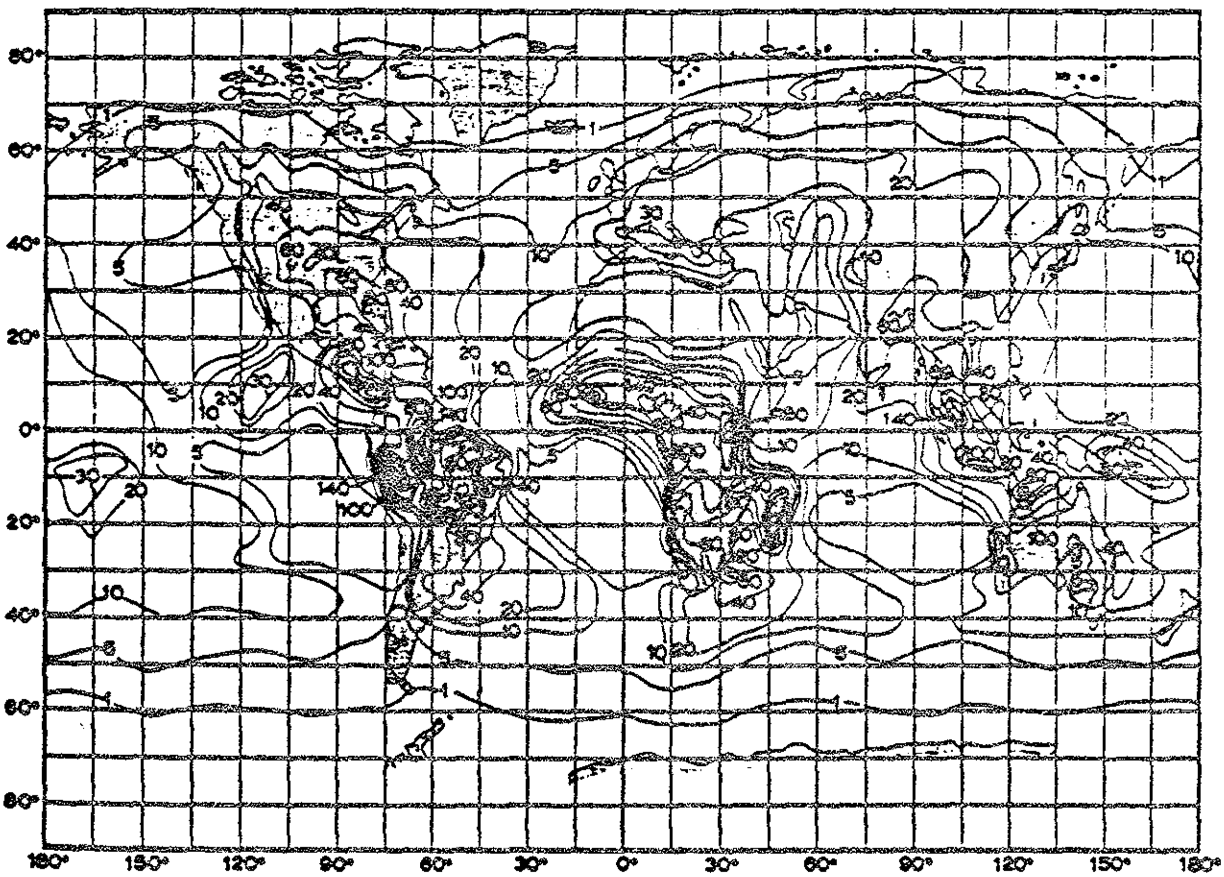


Figure 1. World distribution of isokeraunic levels. Thunderstorm activity is highest near the equator and lowest near the poles [101].

Categorizing Electrical Disturbances

Power system disturbances are voltage and frequency abnormalities of varying duration which are generally considered detrimental from a load perspective, but it is primarily the voltage aberrations which constitute the vast majority of power problems, especially in large, interconnected systems. Although there exist many different types of power system disturbances, almost all are voltage phenomena: either abnormally high or low voltage for varying durations, brief oscillatory pulses or notches superimposed on the AC waveform, or total loss of voltage (blackout). Table 1 presents a list of commonly used definitions of voltage disturbances.

Power Line Voltage Disturbances

	Type I	Type II	Type III
Definition	**Transient and oscillatory overvoltage**	**Momentary undervoltage or overvoltage**	**Outage**
Causes	Lightning, power network switching (especially large capacitors and inductors), operation of on-site loads.	Faults on power system, large load changes, utility equipment malfunction, on-site load changes	Faults on power system, unacceptable load changes, utility or on-site equipment malfunctions.
Threshold level for computer operation.	200 to 400% rated rms voltage or higher (peak instantaneous above or below rated rms.	Below 80 to 85% and above 110% of rated rms voltage.	Below 80 to 85% rated rms voltage.
Duration	Spikes 0.5 to 200 microseconds wide and oscillatory up to 16.7 ms at frequencies of 0.2 to 5 kHz and higher.	From 4 to 60 cycles, depending on type of power system and on-site distribution	From 2 to 60 seconds if correction is automatic, unlimited if manual
	0	0.5	120

Duration (cycles of 60 Hz waveform)

Table 1. Classical definitions of power line voltage disturbances, from [6].

Voltage Disturbances and Transients

Power system transients are relatively short term disturbances which appear as oscillating overvoltages or spikes superimposed on the normal AC waveform. Figures 2 and 3 illustrate two events of longer duration, a complete loss of power (Fig. 2), and a sub-cycle power loss (Fig. 3), which may occur during system faults. The term "transient" comes from the transitory nature of the disturbance and generally refers to deviations in normal voltage for periods of less than one cycle of the 60 Hz voltage, although events of longer duration are often casually included in the general category of electrical transients. Damping of the transient voltage often occurs rapidly so that the resulting disturbance appears as a single spike or notch in the sinewave, depending on the polarity of the leading edge of the initial disturbance. It is therefore the leading edge and the first few decaying half cycles of a disturbance which are of concern for subcycle transients. In an active industrial environment many thousands of transients may occur every hour due do the normal operation of motors, arc welders, solid-state switching circuitry and other common loads.

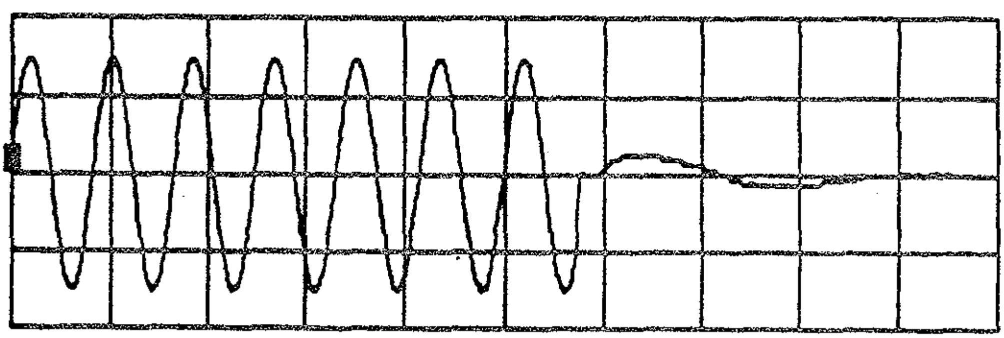


Figure 2. Oscillogram showing long-term loss of line voltage. An uninterruptible power supply is the only power conditioning device capable of protecting essential loads against the long power outages experienced in Alaskan villages.

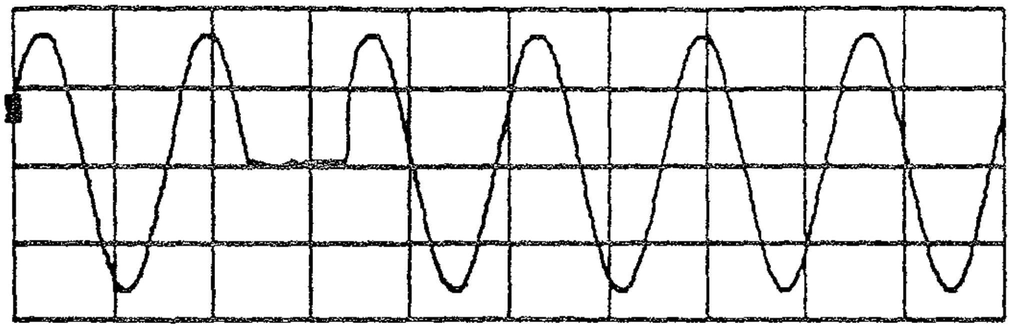


Figure 3. Oscillogram showing 1/2 cycle voltage dropout. Many computers can ride-through a complete loss of voltage for 8 milliseconds.

With the exception of the impulse, definitions of disturbance types have not been standardized but consist of generalized groups of voltage deviations based on duration and on polarity (whether the deviation is additive or subtractive to the 60 Hz wave). Impulses, sags, surges, overvoltages, undervoltages and blackouts (Figs. 2 & 3) comprise the conventional terms used to describe the disturbances which can be expected in a power system. Of these, impulses (fig. 4), sags and surges are generally considered to be transitory, or transients. Sags and surges are special cases of overvoltage and undervoltage conditions where the event duration is at least some significant portion of one cycle (16.7 milliseconds) but less than several seconds.

Overvoltages, undervoltages and blackouts are relatively long-term disturbances and for this reason they are not thought of as transient events, although they may also prove to be harmful to equipment and data.

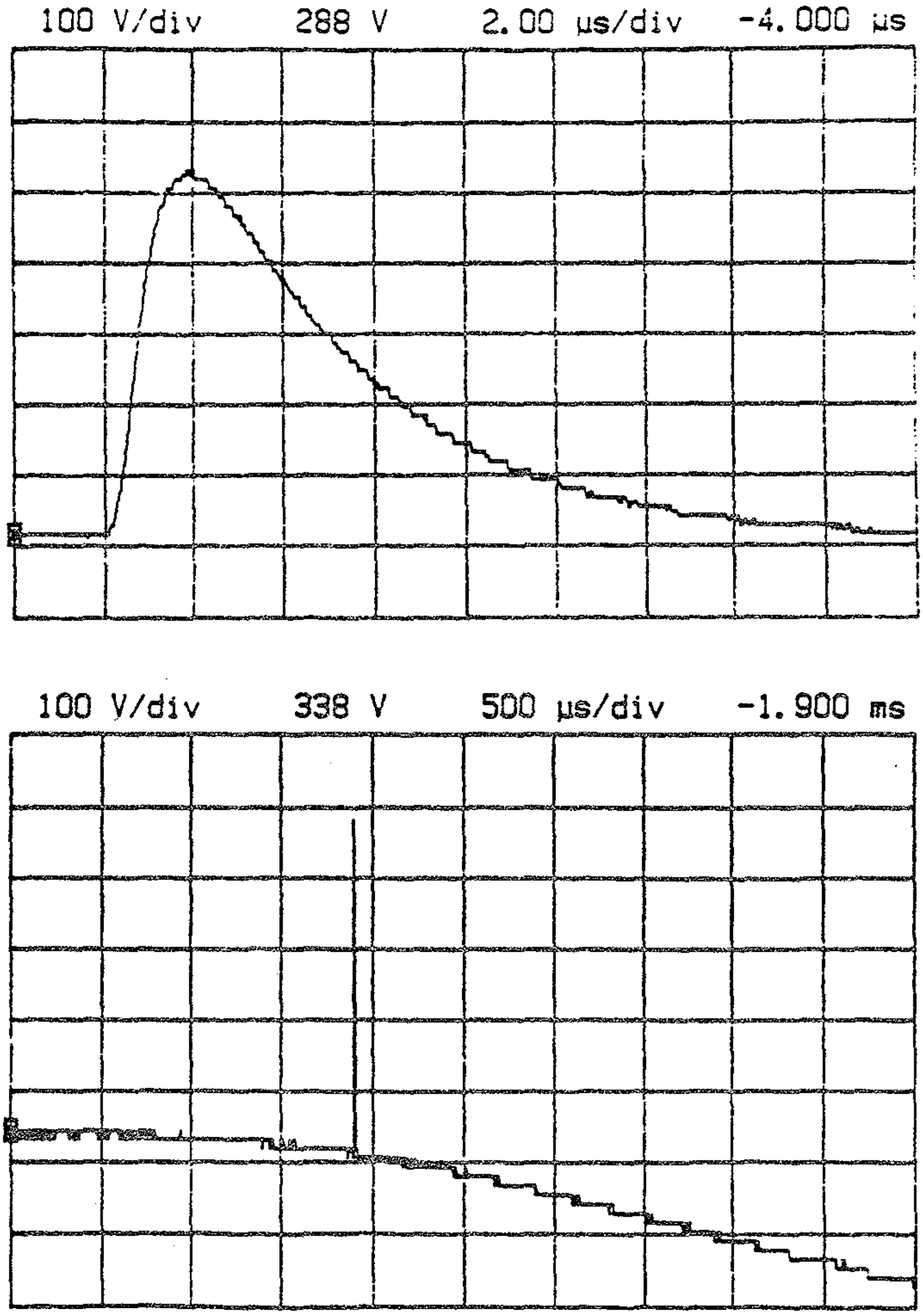


Figure 4. Top: Oscillogram of a 500 V, 2x5μs test impulse of positive polarity used in calibrating commercial line-disturbance monitors. Bottom: The same impulse appears as a spike when inserted near the peak of the positive half-cycle of normal utility voltage.

Frequency Disturbances

Frequency variations are usually neglected in power quality analysis because in a large system the frequency is so closely regulated that it rarely becomes a problem. This is the case in most of the United States where public power is interconnected into large networks with many power sources. Large utilities seldom see frequency deviations of more than 0.5 Hz from 60 Hz, a value within the acceptable limits for computers, motors, and most electronic devices. Even inrush currents to the largest single loads will not shake the frequency stability of the system.

Village power systems with diesel generation do not exhibit the frequency stability found in large systems. Startup of large motors and other substantial loads may cause temporary frequency excursions to as low as 50 Hz or less and increasing loads also cause line frequency to drop. A survey conducted in several Alaskan villages [2] showed that several villages of less than 500 kVA peak loading contain motors in the 5-20 hp range. The inrush current to a 10 hp induction motor represents a substantial load increase to a generator rated at 200 kVA. These loads may be the sources of momentary frequency swings within a 5 Hz bandwidth and can also cause local low voltage conditions at equipment on shared lines.

Sources of Transients

In general, electrical transients are by-products of load variations in the electrical distribution system. Changing loads, switching, fuse operation, relay operation, excitement of magnetic fields, operation of welders, fluorescent lighting and silicon-controlled rectifier operation all contribute to the distortion of the sinusoidal AC waveform.

Under normal utility operation the service to most commercial and residential locations is relatively free from voltage transients. But even if clean AC power arrives at a facility, equipment within the facility can generate troublesome disturbances. Depending on the source of a particular disturbance, its duration can last from a few microseconds to several milliseconds. In most electrical equipment the natural transient frequency is between 500 and 3000 Hz [21]. Rapid damping normally negates all but the first few half cycles and the oscillatory disturbance thus appears as a vertical spike on the AC wave.

The largest source of voltage transients is the switching on and off of inductive loads (motors and transformers), but fast-rising transients of several hundred volts are also generated by solenoids, relays and other switching devices inside most facilities. Industrial environments (solenoids, welding equipment, motors, etc.) will tend to produce more disturbances than residential environments. These disturbances are distributed throughout the facility on grounding systems, power wiring and cable shields so that all equipment within the facility is exposed to some degree.

Residential power circuits are subjected to surge voltages due to two causes:

1. load switching within the house
2. externally generated surges, usually due to lightning or feeder switching.

Internally generated transients tend to be repetitive and can usually be associated with a specific device. Transients near the source (generally less than 50 feet) have fast rising fronts and are rich in high frequency content. Because of the high frequency coupling between conductors these line-to-neutral transients (normal mode) develop line-to-ground and neutral-to-ground (common modes) components as they propagate along a transmission line.

Most electrical household appliances also produce short duration, fast rising transients. Electric typewriters, kitchen appliances, refrigerator and dishwasher motors create spikes which can be several times the the normal line voltage in magnitude and which last for only a few microseconds. The duty cycle of a machine may require that it repeatedly turn on and off during normal operation. Each cycle may introduce voltage transients on the line. Computer loads can also be a source of noise and distortion.

Lightning and EMP

Lightning strikes on or near power lines are known to be a cause of fast-rising transients. This fact has undoubtedly been very good for the power conditioning industry. Microcomputer shoppers have come to assume that the purchase of surge protection equipment is an essential part of a computer system, insuring equipment and valuable data against the "devastating spikes and surges" of advertisement warnings.

The electrical effects of lightning can damage electrical loads. However, the probability of a severe lighting-induced voltage surge varies from one geographical area to another, as was evident in Figure 1. Also, the magnitude of a lightning-induced transient on a transmission line is a function of the stroke location and the magnitude of injected current, as well as many transmission line design parameters. Once the current has been injected into the system it will travel away from the point of insertion along the many possible paths to system ground appearing as a voltage impulse which attenuates rapidly in both magnitude and steepness as distance from the point of origin is increased. Many utility customers may become the recipients of the resulting voltage transients. The electrical effects of the lightning stroke become less as the distance between a customer and the point of origin increases.

Another possible source of transients, primarily of interest in military applications, is the nuclear electromagnetic pulse (EMP). The electromagnetic pulse, caused by a nuclear weapon detonation, can propagate great distances from the point of detonation. The EMP energy from a one megaton weapon detonated at an altitude of several hundred thousand feet would produce electric field strengths on the order of 50,000 volts per meter over wide areas at the surface of the earth facing the detonation [52].

Unlike lightning surges, which are introduced in a power system at a single point and attenuate with distance, EMP-induced transients could appear simultaneously throughout a power system. Induced current pulses of tens of kiloamperes with surge rise times around 10 nanoseconds may occur, exposing entire power grids and communication networks to the effects of a single weapon.

Switching

Most transients occur after a sudden change in current flowing in a circuit or device (switching on or off). In both single and polyphase systems, transients will occur as a function of the instantaneous (not rms) values of voltage and current at the switch during the moment the contacts are open or closed. The severity of the disturbance created by a switching event is therefore dependent not only upon the resistive and reactive properties of the circuit, but also on the precise instant at which switching is performed.

In a rural power system, where switching is normally conducted randomly, the disturbance created when circuit breaker action is applied or when a load is switched will deviate from the theoretical maximum or minimum magnitude for that particular circuit depending upon the positions of the AC voltage and current cycles at the instant of switching. In addition, a closer inspection of a switch opening or closure shows that it typically involves a rapid series of openings and closures which result from bouncing, sliding, rocking, and surface contaminants. Multiple current restrikes (arcing) can occur during this period which can increase the magnitude of the transient.

This phenomenon has undoubtedly been observed by inexperienced linemen while connecting and disconnecting live secondary cables at transformers and distribution connectors in rural systems. This is not a recommended practice from the point-of-view of either power quality or worker safety.

In three-phase systems, transients will almost always occur on at least two phases during switching.

High-energy transients may also appear in a system due to the presence of power factor correction capacitors. In an industrial facility [49] high-frequency oscillatory overvoltages (500 Hz-5 kHz) were measured during capacitor switching which reached 120 percent overvoltage (2.2 per unit at a 460 volt distribution level).

Power System Noise

Undesirable signals come from many sources, usually distinguished as either man-made sources or naturally occurring noise. Anyone who has tuned a radio receiver and heard static or turned on a television and seen "snow" has encountered noise. Naturally occurring noise comes from atmospheric disturbances, thermal circuit noise, and extraterrestrial radiation. These random noise sources are of great concern in communication systems and electronics. Often called "white" noise, this interference is gaussian and has a flat spectral density over a wide range of frequencies.

Although naturally occurring noise is present in any power system, its effect on power line voltage is not significant. In a power system, noise is a more loosely applied term which mainly focuses on the existence of human interference. Man-made interference is, for all practical purposes, random. It also has a wide frequency range and like the true white noise of communications circuits it implies interference with a signal. Power system noise is commonly called EMI (electromagnetic interference) or RFI (radio frequency interference). From the viewpoint of the utility customer EMI and RFI are the same. The term EMI suggests that the interfering signal has been electomagnetically coupled to the distribution lines and has then been conducted through the lines to a sensitive electronic device. RFI simply suggests a relatively high frequency noise signal compared to the 60 Hz waveform, regardless of the coupling path to the receiver.

The procedures necessary to analyze and correct a noise problem are to determine the noise source, the receivers, and how the source and the receivers are coupled together. It follows that there are three ways to reduce, or eliminate the noise. 1) the noise can be suppressed at the source. 2) the noise can be suppressed at the receiver. 3) the noise propagation through the coupling path can be reduced.

Identification of the noise source allows the option of suppressing or isolating the noisy source from all possible receivers, or removing the source altogether. If source identification is not possible then the noise can be suppressed at the receiver.

Common Mode and Normal Mode Noise Signals

Noise signals enter a circuit in either common mode (sometimes called metallic mode or longitudinal mode) or normal mode (sometimes called transverse mode). Transverse mode noise is a voltage signal which exists between the current carrying conductors. In a single-phase system this signal is between line and neutral. Common mode noise appears as a signal common to both current-carrying conductors and is measured between either conductor and ground.

Common mode noise is usually caused by electrostatic coupling where, with equal capacitance between conductors and their surroundings, the induced noise voltages will be the same on each wire. Perfectly balanced common mode noise is rare and most noise voltages will appear having both a common mode and a transverse mode component.

Common mode noise is often blamed for computer and distributed control system errors. Electronic systems which are susceptible to such problems are typically large with many interconnected devices. The system thus becomes prone to voltage potential differences between ground points at the different devices if ground loops inadvertently exist within the extensive interconnections required. Circulating ground currents give rise to common mode voltages at the equipment. For this reason elaborate grounding grids in the form of raised floors have become a standard practice in large computer rooms. By connecting the grid and equipment to a single-point ground a low impedance ground path is provided for high frequency signals minimizing possible interference effects.

Noise should seldom create a problem for isolated computer equipment installed in rural areas, although this may not be true for other sensitive analog equipment. Computers, being inherently noisy devices, require internal filtering to reduce their own contribution to power line distortion. These filters are effective in both directions, keeping noise out as well as keeping noise inside the computer.

CHAPTER 2

POWER QUALITY IN RURAL ALASKA

Characterizing the Village Power System

Providing electric power to Alaska's many remote villages is a formidable task. Very few of these small communities are accessible by road and plant operators frequently lack technical skills. Keeping a power plant running is often a matter of getting crews and materials to a remote site on short notice. Thus, combining transportation difficulties with severe weather conditions often transforms the delivery of fuel and materials into an exercise in logistical wizardry, especially during emergency situations.

Of 113 rural communities surveyed by the Alaska Power Authority, 76 villages had an annual peak power demand of 500 kW or less [2]. Typically, these power systems are composed of two or, more commonly, three diesel generators. Each unit is sized to pick up the entire village load during peak load conditions which occur during the winter.

Although many village power plants are capable of simultaneous and parallel operation of generating units, it is uncommon that this mode of operation is utilized except during brief periods when an incoming unit is synchronized with the running machine to take over the load without interrupting service to the community. Generators are configured to deliver either 208 V, three-phase or 120/240 V, single-phase to a transmission voltage of 7.2 kV, line to neutral. Larger systems may utilize a 480 V configuration.

Transmission conductors are mostly buried concentric-neutral cables or surface cables contained in a metal or wood wireway, depending on local permafrost conditions and availability of heavy equipment. Overhead transmission and distribution systems previously found only in larger rural communities are gradually becoming more prevalent in small power systems in Alaska as advantages in maintenance and safety become recognized and as funds become available.

The Village Electric Load

In a village which generates a three-phase supply voltage there will be few customers which actually receive three-phase service, as nearly all village loads are single-phase devices similar to those found in any U.S. residential area. Normally, where three-phase service is provided, customers might include the city garage, school buildings, the pump house for local water distribution or community watering point, and occasionally the airport facilities. Single-phase 120/240 V, three-wire service is provided to all residential customers. Grounding of the neutral conductor at the service entrance, as required by the National Electrical Code, is standard practice throughout Alaska.

Typical residential loads consist of incandescent lighting, television, audio equipment, refrigerators and freezers, the usual array of hand tools powered by universal motors, and other small household appliances. A typical user of electricity in the villages often does not consider nameplate ratings of equipment prior to purchase. Consequently, utility bills tend to be unpredictable, depending on duty cycles of the various equipment which homeowners have utilized during the previous month.

The use of electric ranges, microwave ovens, and one- or two-burner hotplates are steadily increasing in residences. Small electric heaters abound as a supplement to oil burning stoves- the primary heating source. Industrial power tools, arc welders, and large induction motors are not common residential loads in the villages. In Alaskan villages of up to 500 kVA peak loading it is rare to encounter motors in excess of 10 hp [1][2].

Prior to 1980 few microcomputers were present in rural Alaska. However, the present trend is toward increasing numbers of computers as well as other sophisticated electronic equipment. The scope of equipment being utilized in Alaskan villages now encompasses communications satellite earth stations, computers and office equipment, medical electronics and distributed control systems. Residential electronics have also increased in both quantity and sophistication. High efficiency oil furnaces which operate by microprocessor-controlled circuitry are becoming popular and home computers are no longer an uncommon load.

Power Quality Site Surveys

Site surveys are intended to inventory power line disturbances at a particular location by monitoring utility service lines for voltage and frequency aberrations. The motivation for site surveys usually stems from the presence of electrically sensitive equipment or computers and other microprocessor-based loads. Sensitive equipment may already be in service at the time of the survey or the survey may be of an exploratory nature in advance of the actual installation to indicate whether the electrical environment is safe for both equipment and data. By tallying disturbance events and distinguishing between disturbance types, site surveys may provide information which is helpful in identifying transient sources and the proper selection of power conditioning equipment. Undoubtedly, the results of many site surveys have either not been published or have not been made available to the public. These are most likely studies conducted within private industry to assess the electrical environment in which essential loads are present.

Although the results of several well-known surveys have been widely cited in the literature [4]-[10], these studies may not reflect conditions which occur in unique, isolated systems such as have been installed in Alaska's villages. These suspicions gave rise to the initial rural power quality surveys in Alaska [1]-[3] and village power line monitoring is presently being conducted by the University of Alaska Fairbanks.

Comparisons of the results of different site surveys must take into account the location of disturbance monitoring equipment within the system, the type of monitoring equipment used and the threshold settings which define specific events. Comparing the results of a survey in which an overvoltage threshold was set at 125 volts, for example, to results which implemented a threshold of 135 volts may lead to misleading conclusions when total numbers of surges are compared.

Unfortunately, definitions of power line disturbances have not been standardized and users of commercially available line monitoring equipment tend to adopt terminology consistent with specific labeling conventions of the manufacturers whose line monitors they have purchased.

Tables 3 and 4 show a comparison of the published results of two well-known power quality site surveys [8][9] with the results of data collected in five Alaskan villages [3]. Although differences in types and numbers of certain disturbance events can be distinguished, differences in monitor sense levels and event definitions tend to cloud reconciliation of the surveys.

Rural Power Quality in Alaska

Power line monitoring data for 1,010 monitor-days in four rural communities (Tables 2 through 8) show that those power systems experienced regular frequency swings beyond the ±0.5% tolerance specified by computer manufacturers. It was observed that on 50.3% of the monitor-days the frequency deviated in excess of the ±0.5% figure. On 3.8% of the monitor-days frequency fell to less than 50 Hz. Those low-frequency events generally coincided with 10 second slow-average voltages of around 75% of nominal voltage.

All recorded impulse events were below 400 volts in magnitude. During the 1984 study the largest impulse magnitude recorded was 368 volts at St. Marys, with an average impulse magnitude varying from 120 volts (Ambler) to 262 volts (St. Marys). The overall average impulse magnitude for the four villages monitored during the study was 172 volts.

Location	(total days)	Number of days with maximum impulse between 50V and 99V	Number of days with maximum impulse greater than 99V	Number of impulses during days with 50V to 99V magnitude range	Number of impulses during days with maximum magnitude greater than 99V	Average of monthly maximum impulse magnitudes	Maximum impulse recorded
Ambler	(147)	66 days 44.9%	81 days 55.1%	4,489 68 per day average	5,210 64 per day average	120V	188V
Fort Yukon	(310)	106 days 34.2%	200 64.5%	755 7.1 per day average	2442 12.2 per day average	143V	168V
Kotzebue	(222)	122 days 55.0%	98 44.1%	12,098 99 per day average	1[illegible],533 107 per day average	163V	168V
St. Marys	(331)	66 days 19.9%	264 79.8%	5,796 88 per day average	28,278 107 per day average	262V	368V
Project Total	(1,010)	360 35.6%	643 63.7%	23,138 64 per day average	46,463 72 per day average	172V	368V

Table 2. Impulse disturbance summary from rural Alaska power quality site surveys [1].

Comparison of Power Quality Site Surveys

	Goldstein-Speranza	Allen-Segall	Rural Alaska
Date	1977-1979	1969-1972	1984
Number of Sites	24	29	5
Monitor-months	270	147	32
Sags	7.4%	14.4/month	**
Surges	87%	*	**
Impulses	7.4%	50.7/month	2097/month
Oscillatory	N/A	62.6/month	N/A
Frequency	58.7-60.7 Hz	N/A	***
Outages	4.7%	0.47%	164

* Surges included with sag data in this survey.

** Results tabulated for this survey show that on 78% of the monitor days surge/sag voltages were recorded which fall outside of the +6%, −13% computer tolerance envelope as defined in [6].

*** Survey results show number of monitor-days in which "worst case" frequency deviation exceeds 0.5, 1.0, 2.0, and 10 Hz. On 3.8% of the monitor-days frequency deviation from 60 Hz was greater than 10 Hz.

N/A Disturbance not defined in survey.

Table 3. Comparison of rural Alaska power quality site surveys with the results of two well-known urban surveys [3][8][9].

Disturbance Monitor Sense Levels

	Goldstein-Speranza	Allen-Segall	Rural Alaska
Sags	±5 V	±10 V	±5 V
Surges	±5 V	±10 V	±5 V
Impulses	200 V	30 V	50 V
Oscillatory	N/A	15%	N/A
Frequency	±1/2 Hz	N/A	±1/2 Hz

Table 4. Threshold levels of disturbance monitors used in power quality site surveys [1][8][9].

Inspection of the results of these studies leads to several observations.

1. Tables 3 and 4 show that Allen-Segall survey [8] specifies "oscillatory" spikes, referring to millisecond voltage disturbances with a decaying oscillatory tail whereas the Goldstein-Speranza survey [9] and the Aspnes-Evans-Merritt survey [1] tend to catalogue these disturbances as "impulses."

2. The Allen-Segall and Goldstein-Speranza studies present results which show the total number of impulse events, sag events, outage events, etc., each as a percentage of the total number of events recorded during the survey. The Aspnes-Evans-Merritt study, recording significantly greater numbers of events in small, isolated systems, present "worst case" data which shows, for example, that out of 1,010 power line monitor-days an impulse of greater than 99 volts was recorded during 643, or 63.7% of the monitor-days.

3. The Aspnes-Evans-Merritt study defines an impulse as having a duration of 0.5-800μs, whereas the Goldstein-Speranza study defines an impulse as having a duration of 0.5-100μs. Both studies apparently employed the same model of surge monitor.

Location	(total days)	Deviation range Δf (hz) Δf ≤ 0.5	0.5 < Δf ≤ 1.0	1.0 < Δf ≤ 2.0	2 < Δf ≤ 10	Δf > 10
Ambler	(147)	13 days 8.8%	100 68.0%	23 15.7%	7 4.8%	4 2.7%
Fort Yukon	(310)	271 days 87.4%	7 2.3%	12 3.9%	19 6.1%	1 0.3%
Kotzebue	(222)	31 days 14.0%	146 65.8%	20 9.0%	10 4.5%	15 6.8%
St. Marys	(331)	187 days 56.5%	89 26.9%	12 3.6%	25 7.6%	18 5.4%
Project Total	(1,010)	502 days 49.7%	342 33.9%	67 6.6%	61 6.0%	38 3.8%

Table 5. Number and percentage of days with worst-case frequency deviation within specified ranges for rural Alaska site surveys [1].

Location	(total days)	Voltage Ranges (%) -100% → -40.1%	-40% → -20.1%	-20% → -13.1%	-13% → +6%	+6.1% → +10%
Ambler	(147)	0 0%	8 5.4%	16 10.9%	113 76.9%	10 days 6.8%
Fort Yukon	(310)	5 1.6%	11 3.6%	32 10.3%	262 84.5%	0 days 0%
Kotzebue	(222)	1 0.5%	3 1.4%	5 2.3%	0 1.4%	221 days 99.5%
St. Marys	(331)	1 0.3%	54 16.3%	180 54.4%	93 28.1%	3 days 0.9%
Project Total	(1,010)	7 0.7%	76 7.5%	233 23.1%	468 46.3%	234 days 23.2%

Table 6. Number and percentage of days with worst-case slow average voltages within specified ranges above and below system nominal in rural Alaska [1].

Location	(total days)	Voltage Ranges %					
		-100% → -40.1%	-40% → -20.1%	-20% → -13.1%	6% → 9.9%	10% → 20%	>20%
Ambler	(147)	0 0%	1 0.7%	69 46.9%	13 8.8%	4 2.7%	1 day 0.7%
Fort Yukon	(310)	14 4.5%	35 11.3%	248 80.0%	0 0%	0 0%	0 day 0%
Kotzebue	(222)	2 0.9%	4 1.8%	25 11.3%	36 16.2%	50 22.5%	2 days 0.9%
St. Marys	(331)	5 1.5%	32 9.7%	247 74.6%	2 0.6%	2 0.6%	0 day 0%
Project Total	(1,010)	21 2.1%	72 7.1%	589 58.3%	51 5.0%	56 5.5%	3 days 0.3%

Table 7. Number and percentage of days with worst-case sag/surge voltages within specified ranges above and below system nominal for rural Alaska [1].

Location	(total days)	Known duration outages	Total outages	Total known duration outage time (hours)	Average outage duration (minutes)	Average number of days between outages
Ambler	(147)	13	35	2.39	11.0	4.2
Fort Yukon	(310)	15	17	45.8	183.0	18.2
Kotzebue	(222)	12	13	1.15	5.8	17.1
St. Marys	(331)	95	99	11.4	7.2	3.3
Project Total	(1,010)	135	164	60.7	27.0	6.2

Table 8. Power outage summary for rural communities as reported in [1].

Whenever small local generation is involved, the high transient impedances of the generators become evident during the load starting interval and can aggravate the voltage drop that is ultimately realized. Worst case sag/surge data presented in Table 7 show that during 78% of the total monitor-days the per cycle rms voltage exceeded the +6% and -13% limits normally specified by computer manufacturers. Daily worst-case sags between -13% and -20% occurred on 58.3% of days monitored. Sags below -20% and/or surges above +10% of nominal (120V) occurred during 15% of all days monitored.

Frequent outages of long duration are a primary concern in rural villages as has been confirmed in [1]. The average power outage found during this survey was 27 minutes over a total of 135 outages of known duration. Excluding two outages which contributed 36.5 hours, the adjusted average falls to 10.9 minutes per outage. This value exceeds the battery backup capabilities of many uninterruptible power systems operating under full load conditions.

The average outage duration varied considerably between villages as is shown in Table 8. The average number of days between outages is likewise varied. Fort Yukon, which experienced two outages totaling 36.5 hours, has an adjusted average of 42.7 minutes per outage (covering 13 outages) if these two events are excluded from the data.

The frequency of occurrence and duration of outages in rural communities should be a significant factor in considering power conditioning alternatives where continuity of supply is important. Differences in outage frequency and duration between small Alaskan communities and large interconnected power grids is apparent when comparing the Alaska study [1] with the Allen-Segall study [8], where an outage rate of 0.6 outages per month with an average duration of 1.0 minutes was reported.

Frequency stability is a problem unique to small generating plants and has been shown to occur in Alaskan systems. This is most likely caused by switching in large portions of the village load at the power plant, or in some cases by the starting of large motors or other individual loads. Severe low-frequency excursions usually coincide with sagging voltage and can be a cause of motor burn-out and other load malfunctions during these events.

Power Conditioning Requirements for Village Loads

Power quality data in several rural villages show that frequent low voltage/low frequency swings occur in rural power systems which exceed the tolerances of many electronic devices. This type of disturbance probably accounts for the majority of equipment failures, although documentation of electrical damages in rural power systems is rare and possibly limited to the information collected by a survey of village power plant operators in [2].

This problem occurred in varying degrees within the villages studied but it is likely that all small, isolated systems regularly experience voltage sags due to the inability of relatively small diesel generators to deliver sufficient inrush currents to loads during start-up. Voltage regulation would therefore be advantageous where voltage sensitive loads are to be installed.

One possible alternative to voltage regulation for noncritical yet sensitive loads might be a simple device which detects rms voltage level at the load and drops power to the device if system voltage swings outside of acceptable levels. At least one company in Alaska manufactures a device which will detect unacceptable voltage levels, switch off power to the load upon detection of such an event, and upon restoration of normal voltage, delay repowering the load by several seconds in order to allow utility power to stabilize. This unique type of strategy may be very useful in protecting against damaging voltage fluctuations which occur in small systems. Deep sagging voltage and frequency are the electrical disturbances which should be of most concern to rural residents due to possible damage to electric motors.

Under low-frequency conditions, induction and synchronous motors may be overexcited and overheat if the voltage is not reduced accordingly. Most loads are speed sensitive, and motor overloading will usually not occur due to low frequency. But if the shaft load remains constant during low frequency, the motor may be overloaded during the event. Operation at a constant volts per hertz is the criterion. Reduced line voltage without a corresponding reduction in frequency will cause increased slip in induction motors and increased armature current under constant shaft torque, again leading to possible overheating.

Blackouts in rural systems, though not damaging, are obviously a concern where continuous power to loads is essential. Noncritical loads, by definition, can be safely disconnected from the power supply. Equipment damages associated with power failures would most likely occur during the first few seconds following restoration of power when large sections of the village load are being reconnected to the supply.

A high occurrence of impulse voltages with magnitudes between 50 and 100 volts have been measured in small Alaskan systems. The effects of these disturbances is not known, but the relatively large numbers of impulse disturbances in villages compared to the urban studies may warrant surge suppression for valuable electronic equipment. However, it is also likely that the relatively high numbers of impulses recorded in Alaska are due to the proximity of disturbance monitoring equipment to specific loads which are disturbance sources. Electrical damage to equipment in villages has been blamed on voltage "spikes" and this may be the case. Impulse voltages of low magnitude may degrade semiconductor components over a long period of time eventually causing failure. High magnitude impulse voltages may also occur, although none above 400 volts have been recorded in Alaskan studies.

Lightning-related surges may be of less concern due to the low incidence of thunderstorms in Alaska and to the small amount of electrical hardware which rural power systems expose to the storm. Where power conditioning equipment is deemed necessary to protect certain loads from the other village disturbances then proper selection among the power power conditioning alternatives can also incorporate adequate lightning protection.

CHAPTER 3

ISOLATION, VOLTAGE REGULATION AND POWER CONDITIONING

Introduction

Isolation transformers, voltage regulators and power conditioners constitute a large part of the available equipment which are used to mitigate certain undesirable power line abnormalities. Since these are all transformer-based devices they can be appropriately placed in the same general category for comparison although it is only the latter two which actually regulate voltage.

When investigating these transformer-based devices it must be recognized that within this group only two functions are normally provided: isolation and voltage regulation. The term *power conditioner* implies a voltage regulating device which also provides some degree of isolation between primary and secondary windings. The merits of isolation and voltage regulation are discussed in detail in following sections.

Slow Voltage Fluctuations

Fluctuating voltage or steady state voltage deviations from nominal levels can affect the normal operation of electronic equipment and electric motors. Possible causes of voltage fluctuations in rural Alaskan systems can include the following.

1. heavy inrush currents during changing loads or motor start-up.
2. excessive line voltage drop between distribution transformers and the customer's service entrance due to long secondary conductors.
3. improper balancing of phase loads or improper switchgear loading at the plant, causing momentary generator overload during start-up.
4. improper voltage settings at the power plant.

Brownouts, intentional low voltages initiated by utilities during periods of high power demand, are not a practice in rural Alaska, although the village equivalent of brownout conditions may occasionally and unintentionally occur if careful monitoring of system voltage is neglected.

Slow voltage fluctuations occurring at a sensitive load can be corrected with the use of one of several types of voltage regulators or by installing a dedicated line in certain circumstances. A dedicated line can be an inexpensive and effective solution if voltage sags are known to be caused by startup currents to motors on shared lines with other equipment.

Voltage Regulation and Power Conditioning

Most voltage regulators are incorporated into a classification called *power conditioners*. A power conditioner, by convention, is a voltage regulator whose power transformer has separate primary and secondary windings. The two windings are said to be isolated, therefore the regulator is also an isolation transformer.

Following the convention, a *voltage regulator* does not possess separate windings but uses a single winding, a portion of which is common to both primary and load currents. This configuration describes the standard autotransformer and herein lies the physical difference between voltage regulators and power conditioners. A power conditioner is simply a voltage regulator which has received a upgrade in title by virtue of offering isolation.

Because isolation is sometimes advantageous single-winding voltage regulators are on the decline in popularity and availability. For the purposes of this discussion, however, the term *voltage regulator* will be used to describe both devices in recognition of it's primary function.

Ferroresonant Transformers

Ferroresonant transformers have been used since the early 1930's as a voltage regulating device. The ferroresonant transformer is one of the simplest and most reliable methods of power conditioning available, although it lacks in efficiency when compared to other transformer-based devices (Fig. 5). It contains no moving parts

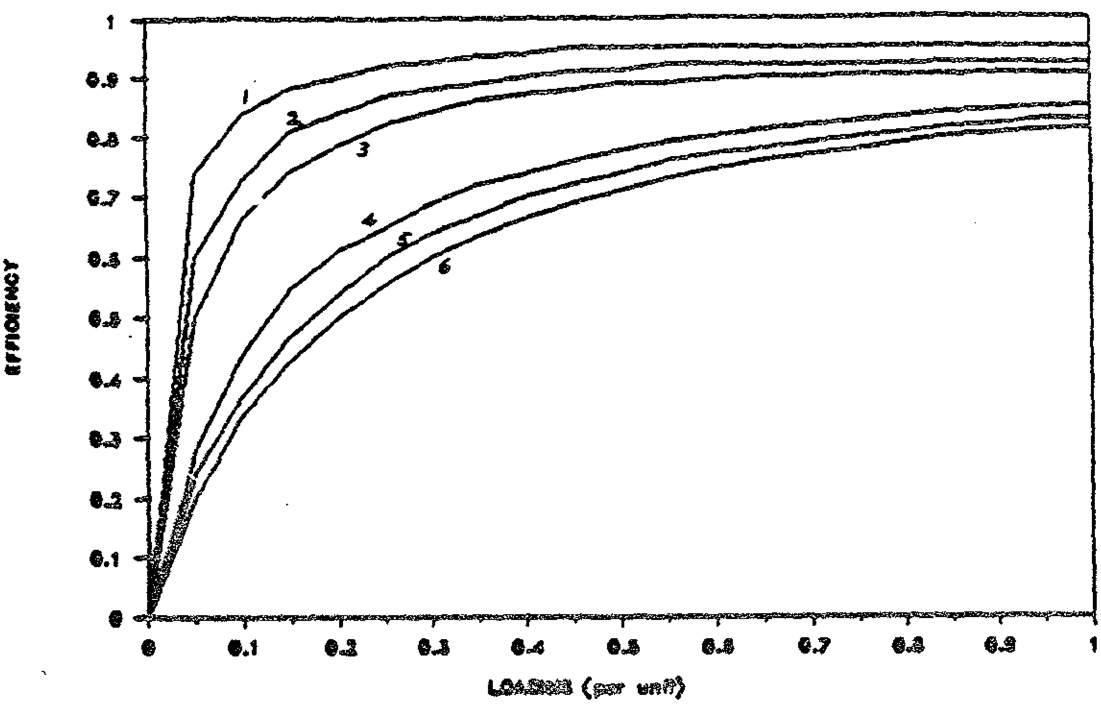


Figure 5. Efficiency comparison of transformer-based power conditioners. 1) 1000 VA tap-changing conditioner. 2) 500 VA isolation transformer. 3) 500 VA tap-changing conditioner. 4) 500 VA ferroresonant transformer. 5) 500 VA ferroresonant transformer 6) 500 VA ferroresonant transformer.

or sensitive electronic components and therefore represents a unique class of AC voltage regulating equipment by virtue of its simplicity and ruggedness.

Also known as Constant Voltage Transformers (CVTs), ferroresonant transformers are designed to hold output voltage constant for a wide range of input voltages. This is accomplished by operating the transformer secondary core in flux saturation during the peak of every half cycle for input voltages greater than approximately 75 percent of nominal. The output voltage is then limited to small changes once the input voltage exceeds the value required to saturate the secondary core, irrespective of changes in input voltage, as long as the secondary core gets saturated in each half cycle. Saturation in the secondary is achieved by adding a capacitor across the output windings. This creates a tuned circuit in the secondary which, combined with

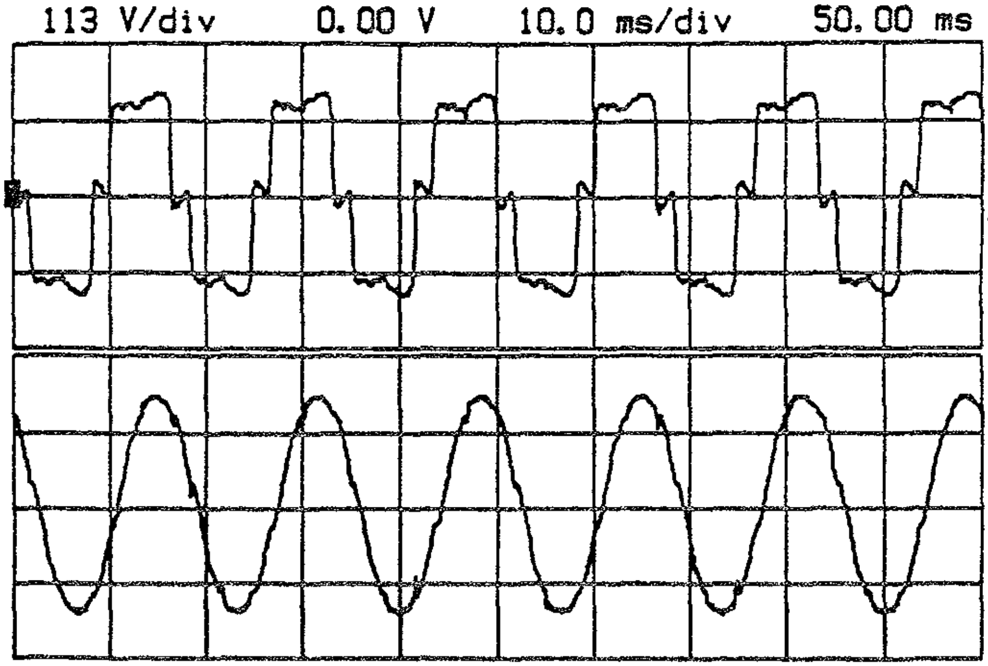


Figure 6. The lower oscillogram shows the filtered output of a Sola 500 VA ferroresonant transformer. The input (top) was a 120 V_{rms} stepped-wave produced by a 300 VA UPS inverter.

a modified core structure, increases the flux in the secondary core path allowing the secondary to attain flux saturation while the primary remains unsaturated.

Ferroresonant transformers are excellent at regulating voltage and suppressing both common mode and normal mode line noise. They provide good isolation from common mode noise due to the physical separation of the primary and secondary windings, and good normal mode protection because normal mode transients get clipped in the saturated secondary. For this reason they are often referred to as ferroresonant power conditioners. Figure 6 illustrates the normal mode filtering of a stepped-wave when input to the ferroresonant transformer. In this instance, the stepped-wave represents the output of a 350 VA uninterruptible power supply. Typical values of noise attenuation in a ferroresonant transformer are 120 dB common mode rejection and 60 dB normal mode rejection.

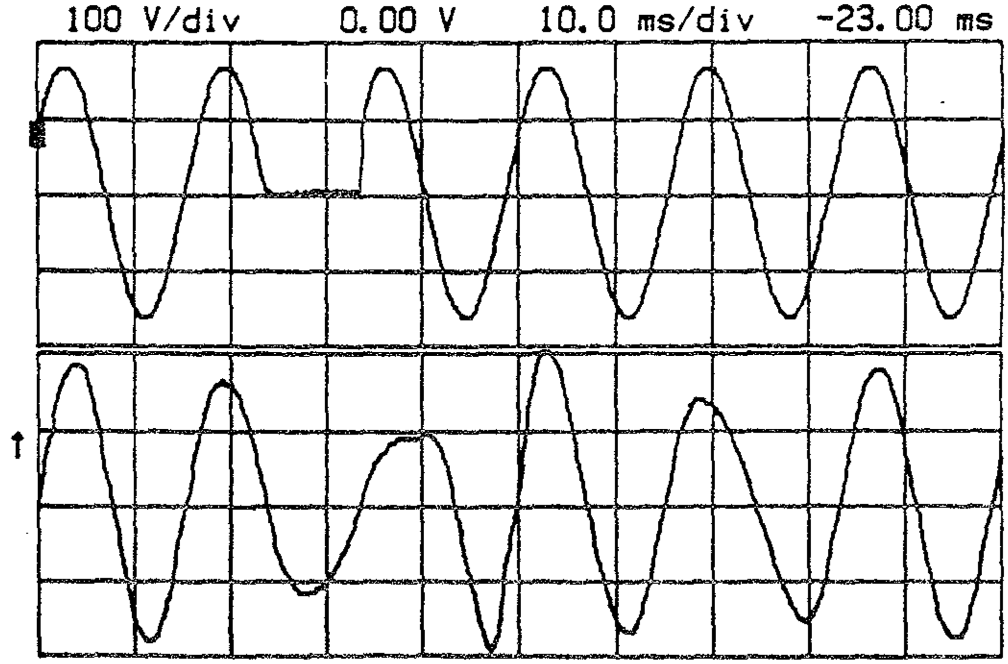


Figure 7. Inherent energy storage in the LC tank circuit of the Sola 500 VA ferroresonant transformer allows sensitive loads to ride through subcycle power interruptions (top).

The tuned circuit in the secondary has several consequences in affecting unit performance. Ferroresonant transformers are notoriously frequency sensitive. Typically, output voltage will change by 1.5 percent for a 1 percent change in frequency of the input voltage. Ferroresonant transformers are also less efficient than nonsaturating transformers and typically draw 15 percent of rated current at no load.

One advantage of the resonant circuit is the ability to ride through millisecond interruptions of the supply voltage (Figure 7). Depending on the particular design, a ferroresonant transformer can store sufficient energy to cover up to 3/4 cycle interruptions of the input voltage.

Ferroresonant power conditioners typically have high impedances and are sensitive to load power factor. They have excellent overload characteristics and will self-limit output current to less than 200 percent of rated current under output short circuit condition. Output voltages are normally high in harmonics because of the saturated secondary. Three to five percent harmonic distortion is typically added to the input waveform through the device. Ferroresonant transformers also tend to operate hotter than nonsaturating transformers and at a slightly higher audible noise level.

Electronic Tap-Changing Regulators

Tap-changing voltage regulators and conditioners operate by monitoring the output voltage of a tapped transformer and making adjustments by solid-state switching of transformer taps. Figure 8 illustrates the regulating characteristics of a 1 kVA tap-changing device compared to that of a ferroresonant transformer. Tap-changing regulators, as opposed to conditioners, utilize an autotransformer which does not provide isolation from common mode noise. The term "conditioner" implies both regulation and high common mode rejection. When purchasing a voltage regulator its noise limiting specifications should be obtained from the manufacturer if they are not included in the initial specifications provided. Most power conditioners rival high isolation transformers in noise attenuating capability and therefore function well as both voltage regulating and common mode noise isolating devices.

Like other transformer-based power conditioning equipment (ferroresonant and isolation transformers), as well as line surge suppressors, electronic tap-changing regulators do not provide protection against power failures. A reduction in service voltage of greater than 30% is generally considered to be a power failure and a problem which cannot be resolved by voltage regulation.

Tap-changing regulators and conditioners generally provide little protection from half-cycle loss of input voltage unless special provisions such as added capacitors have been included. As seen in figures 9 and 10, two tap-changing power conditioners were subjected to the half-cycle voltage dropout test. One of the conditioners provides minimal protection from the brief voltage loss. The conditioner represented by the oscillogram of figure 10 contained an internal capacitor bank supplying sufficient energy to supplement the short term voltage loss. The capacitors are provided with this type of disturbance in mind.

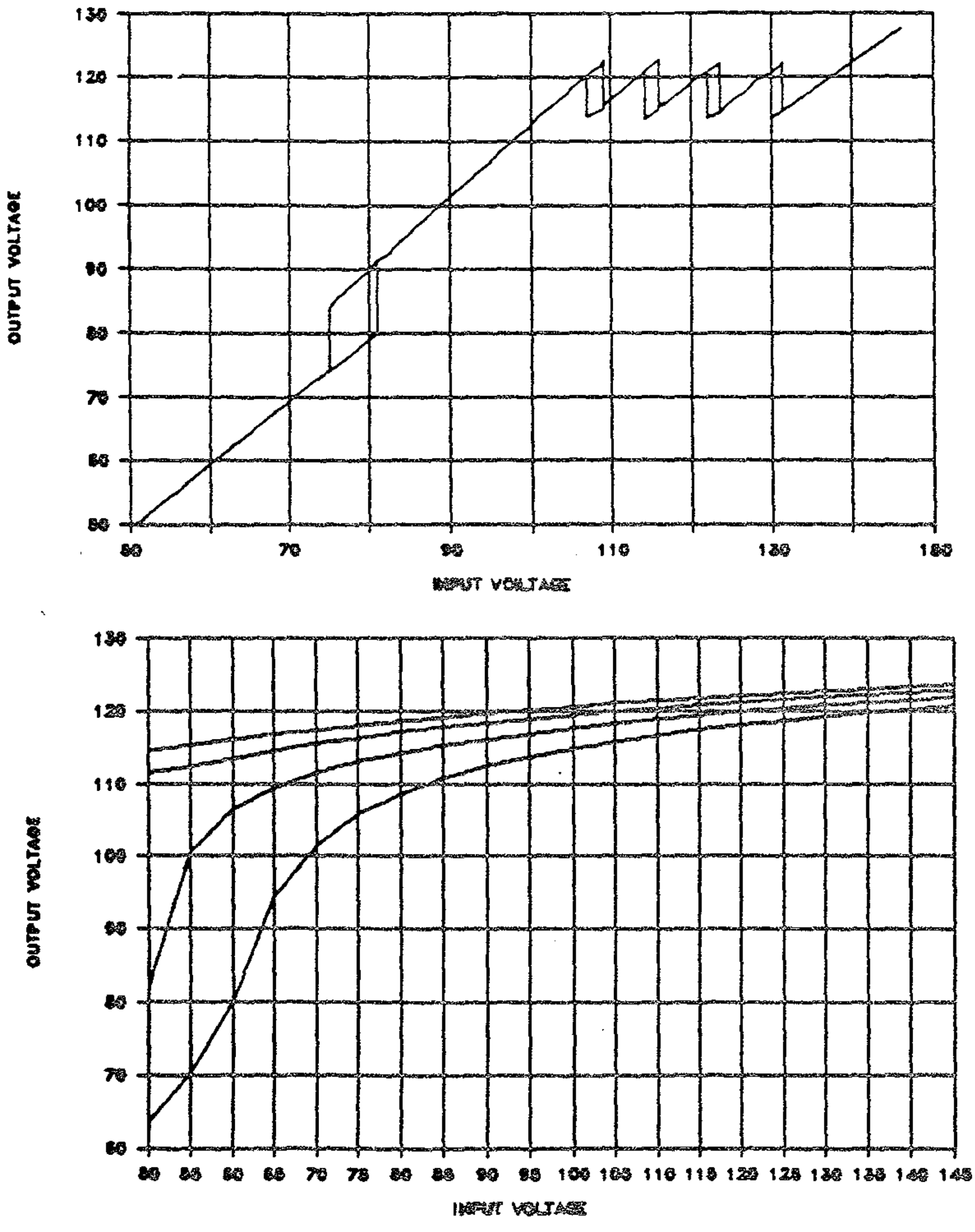


Figure 8. Typical voltage regulation characteristics of a tap-changing voltage regulator (top) and a ferroresonant regulator (bottom). Ferroresonant regulation improves as the load is reduced.

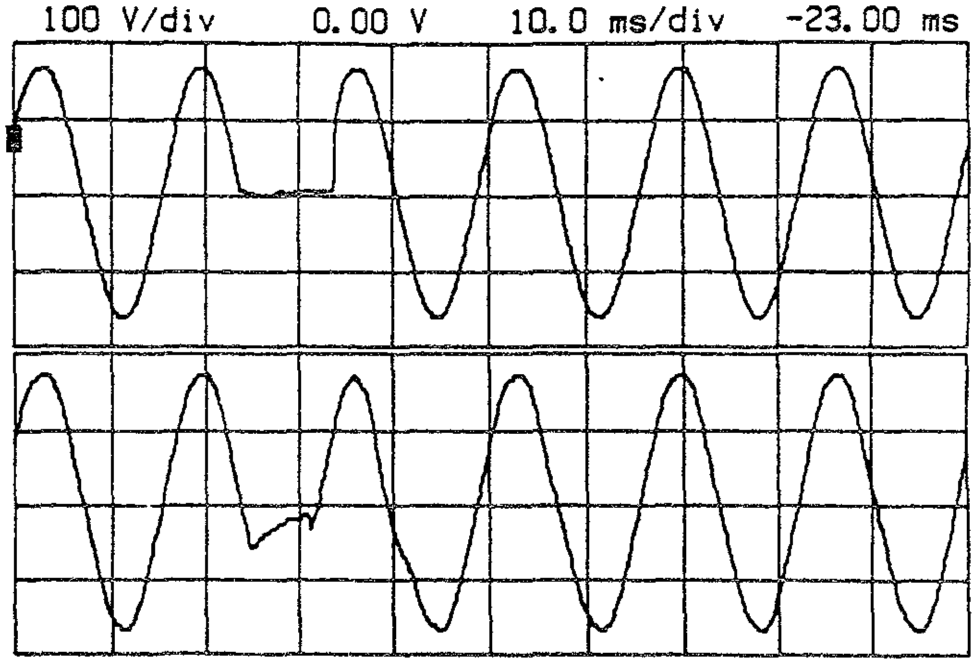


Figure 9. Top: 1/2 cycle voltage dropout disturbance. Bottom: 1/2 cycle dropout appears at the output of a 500 VA tap-changing power conditioner without internal capacitance.

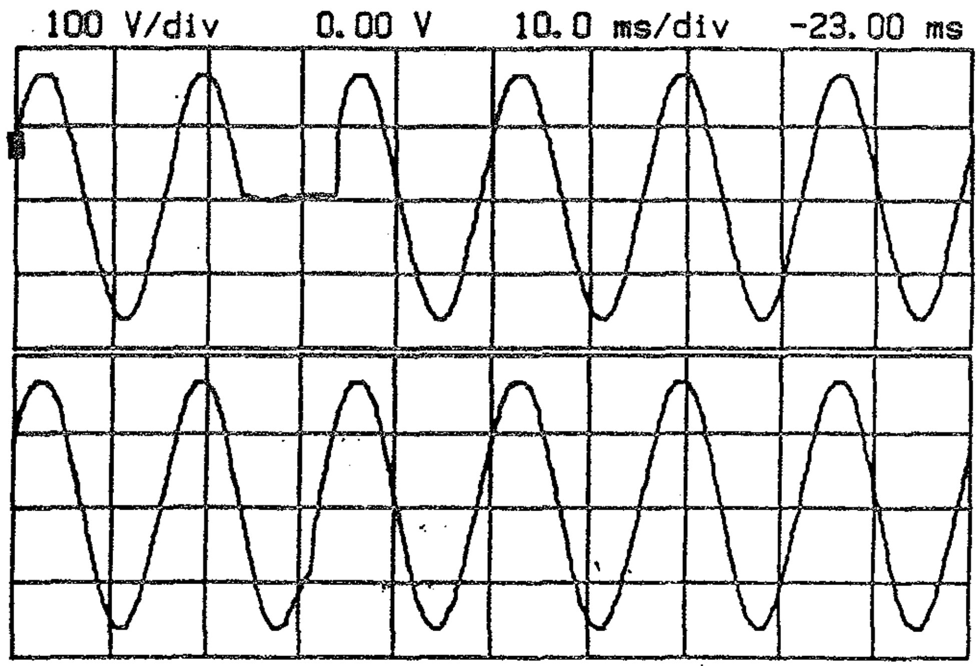


Figure 10. Top: 1/2 cycle dropout disturbance. Bottom: Capacitors incorporated in the design of this 1000 VA tap-changing power conditioner store sufficient energy to ridethrough subcycle voltage loss.

The advantages of tap-changing regulators and conditioners are low impedance, low distortion and high efficiency. Low internal impedance is desirable for applications in which high inrush currents must be supplied to motors during starting. Tap-changing regulators can deliver in excess of ten times rated current for one cycle and typically three times rated current for ten seconds. Constant voltage transformers, which self-limit overload current to less than 200%, may need to be oversized where high inrush currents are expected. The low output distortion of tap-changing regulators is also an advantage where a smooth sinusoidal output wave shape is desired. A high harmonic content in the supply voltage can cause vibrations in motors and power supply transformers. It will also give rise to higher operating temperatures which can result in shortened operating lifetimes.

Tap-changing regulators respond very quickly to changes in input voltage. Typically, a single tap change is performed in one-half cycle and full correction to a voltage fluctuation is made within 2 cycles. Switching is normally accomplished with silicon-controlled rectifiers or triacs which are triggered by a microprocessor-based control circuit. The tap switching devices do generate internal noise within the regulator that can appear at the output if not properly filtered. Switching will normally occur at the first current or voltage zero crossing following the sensing of a low or high voltage condition. If zero-voltage switching is used, a power factor limitation will usually be imposed on the device in the specifications. Zero-current switching will remove power factor restrictions and reduce internally generated transients resulting from current chopping in the transformer secondary.

Isolation Transformers

Isolation transformers are shielded power transformers which isolate an electrical load from common mode noise and transients. They have often been considered to be the most economical and efficient solution to power line noise problems in computer installations but this opinion is only valid under the assumption that all noise appears in the common mode where the transformer is most effective. The degree of protection is inversely proportional to the noise frequency. An isolation transformer will therefore be less effective for very high frequency disturbances.

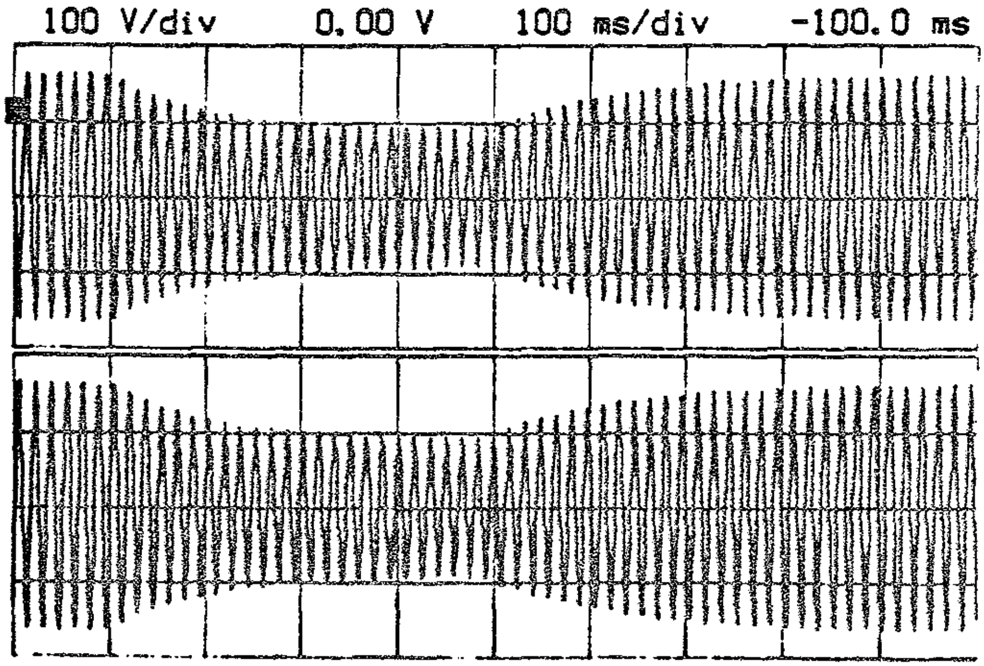


Figure 11. Oscillogram of typical isolation transformer response to a deep sag voltage to 70 V_{rms}. The top waveform represents the power line sag voltage. The lower waveform shows unaffected output of the isolation transformer.

Isolation transformers are similar to standard power transformers in that they can be used to step up or step down a voltage to a desired level and then isolate, or they can be used in a one-to-one voltage non-transformation strictly to isolate a particular load from the noise source. It should be emphasized that a noisy source can also be isolated in the same manner. Isolation is a bilateral attribute. It can effectively work in both directions, but whether to isolate a sensitive device which is susceptible to noise or to isolate the noise source is a judgment call and requires knowledge of the source(s) and receiver(s) as well as identification of the noise coupling channel.

Isolation transformers are not voltage regulating devices and should not be mistaken as such when power conditioning is being considered. Although normal mode disturbances are attenuated somewhat at the higher frequencies, slow average high or low voltages, brownouts, blackouts and frequency disturbances will appear at the transformer output unaffected by the presence of this device. Figure 11 illustrates the output of an isolation transformer when subjected to a severe line voltage sag.

Most transformers, excluding autotransformers, isolate the input from the output circuit to some degree. The primary and secondary windings are electrically isolated in the sense that primary current does not appear in the secondary windings. It is by magnetic induction that the transformer functions. However, electrostatic (capacitive) coupling between the primary and secondary windings allows high frequency common mode noise signals to penetrate the secondary. There is no magnetic coupling because common mode voltages do not impress any line-to-line or line-to-neutral voltages across the primary.

A high capacitance existing between the input and output windings means a greater susceptibility to common mode noise propagation through the transformer and therefore less isolation. If a nonmagnetic, conductive shield is placed between the windings and connected to the circuit ground then the interwinding capacitance is reduced and a higher degree of electrostatic isolation is achieved. This technique describes the basic construction of an isolation transformer.

A very typical value of common mode noise rejection provided by an isolation transformer is 120 dB. High isolation, super isolation, or ultra-isolation are nonstandard terms which are intended to emphasize the degree of isolation provided by specific models which exceed the standard 120 dB value by employing double or triple shielding. Some manufacturers claim that extra shielding can increase common mode noise rejection to greater then 150 dB, approximately 40 million to one.

An isolation transformer that is put into service to protect a sensitive load should be positioned as close to the load as possible. This reduces the possibility of common mode voltage pickup by electromagnetic radiation into power lines between the transformer and the load.

Isolation transformers are extremely efficient. Typical values are 96-98 percent at full load. But they do not provide voltage regulation, protection from power outages or suppression of most normal mode transients.

Features of AC line Protection Devices

Device	Description	Voltage Regulation	Frequency Regulation	Blackout Protection	Normal mode Transient Protection	Common Mode Transient Protection
Surge Suppressors	Typically, semiconducting devices configured to divert or filter surges upstream from loads	None	None	None	Good. Even the cheapest models will suppress fast line-to-neutral transients.	Generally, the more expensive models tend to provide common-mode protection.
Shielded isolation transformers	A transformer with isolated, electrostatically shielded primary and secondary windings.	None	None	None	Low. Transients may be band limited but most will get through.	Good. 120 dB common mode is typical.
Tap-changing conditioners	A shielded isolation transformer which regulates voltage by automatically changing secondary winding taps.	Good. Output voltage is held near nominal for a 25% drop in input voltage.	None	None	Low, unless additional filters or suppression component are included.	High. Typically as good as an isolation transformer
Ferroresonant transformer	A shielded isolation transformer operating with a saturated secondary winding.	Good. Approximately equivalent to tap-changing devices at rated load. Regulation improves under partial load.	None	Ferros will release stored energy to cover many subcycle power interruptions.	Good. The saturated secondary clips most normal mode transients.	High. Typically as good as an isolation transformer
Uninterruptible power system	A solid-state inverter powered by storage batteries.	Fair. The inverter kicks in when line voltage drops below a preset value.	Fair if voltage drops in proportion to the frequency.	High. The duration of protection depends on battery capacity.	Total isolation only when the UPS inverter is operating.	Total isolation only when the UPS inverter is operating.

Table 9. A comparison of commercially available power conditioning devices typically in use for computers and sensitive loads.

Dedicated Lines

When the merits of power conditioning apparatus are being discussed the topic of dedicated circuits occasionally arises. A dedicated line is simply one which is dedicated to serve a specific load. No other devices or outlets are served by the dedicated branch. The installation of dedicated lines to sensitive loads can often be an effective and inexpensive solution to certain powerline problems but it is important to understand what those problems are and what one is trying to achieve before implementing this particular power conditioning strategy.

A dedicated line is primarily intended to reduce line voltage drop by reducing the total loading on the line. A computer sharing a branch circuit with a large motor, for example, can shut down during motor starting cycles due to excessive line drop as the motor draws initial inrush current. The computer will normally reboot as the motor gains speed but valuable information may be lost in the interim. A dedicated line also avoids power interruptions to critical loads due to faults caused by other loads tripping the circuit breaker.

The dedicated circuit must not be shared with large motors or other switched inductive loads. Load switching causes transients which are attenuated as they propagate along the line. Without expensive power conditioning equipment, it is a matter of increasing the distance between a source of transients and a sensitive load to reduce their amplitude and fast rise-times. A shared line implies short distances between loads and allows them to pass transients from one to the other with little attenuation. A dedicated line from a sensitive device to the service entrance will reduce the effect of transients generated within the facility. Similarly, a line dedicated between a load and the distribution transformer will put ever greater distances between the load and internally generated transients. Ultimately, point of connection of a dedicated circuit is a judgment call based upon knowledge of the specific system and the costs of additional lines which the user is willing to accept.

CHAPTER 4
IMPULSE SUPPRESSION

Introduction

The goal of impulse suppression is to protect electrical loads from high magnitude, short duration transients. Lightning-induced disturbances are emphasized as the primary cause of impulse voltages in the order of several thousand volts but impulses several times the line voltage in magnitude can also be produced by inductive loads such and welders, air conditioning equipment, motors and many industrial loads.

The power conditioning industry provides a multitude of solid-state, indoor impulse suppressing devices designed to safeguard against catastrophic damage to electrical equipment in the event of a large impulse voltage on the power leads to sensitive loads.

Surge Suppressors

Surge suppressors[1] are relatively inexpensive shunt devices and power line filters which are normally sold as microcomputer protection equipment. They are the small plug-in devices purchased from the computer retail supplier which are intended to protect microprocessor-based equipment from damaging impulse voltages at the wall outlet. Their function is to limit high voltage transients before they reach the computer power supply.

The more effective suppressors utilize a combination of electrical components to shunt, or short circuit the impulse before it can reach the equipment. These "hybrid" suppressors, two possible configurations of which are shown in Figure 12, evolved through the realization that there is no single component which can do the job well if unassisted. They therefore combine two or more technologies to provide transient suppression over a wider range of voltages, rates of rise, and energy content.

[1] The reader should be aware that this term may seem inconsistent with other uses of the term "surge" in this report. Computer surge suppressors are impulse suppressing devices, emphasizing high magnitudes and short-duration events. Refer to Table 1 for generalized disturbance definitions.

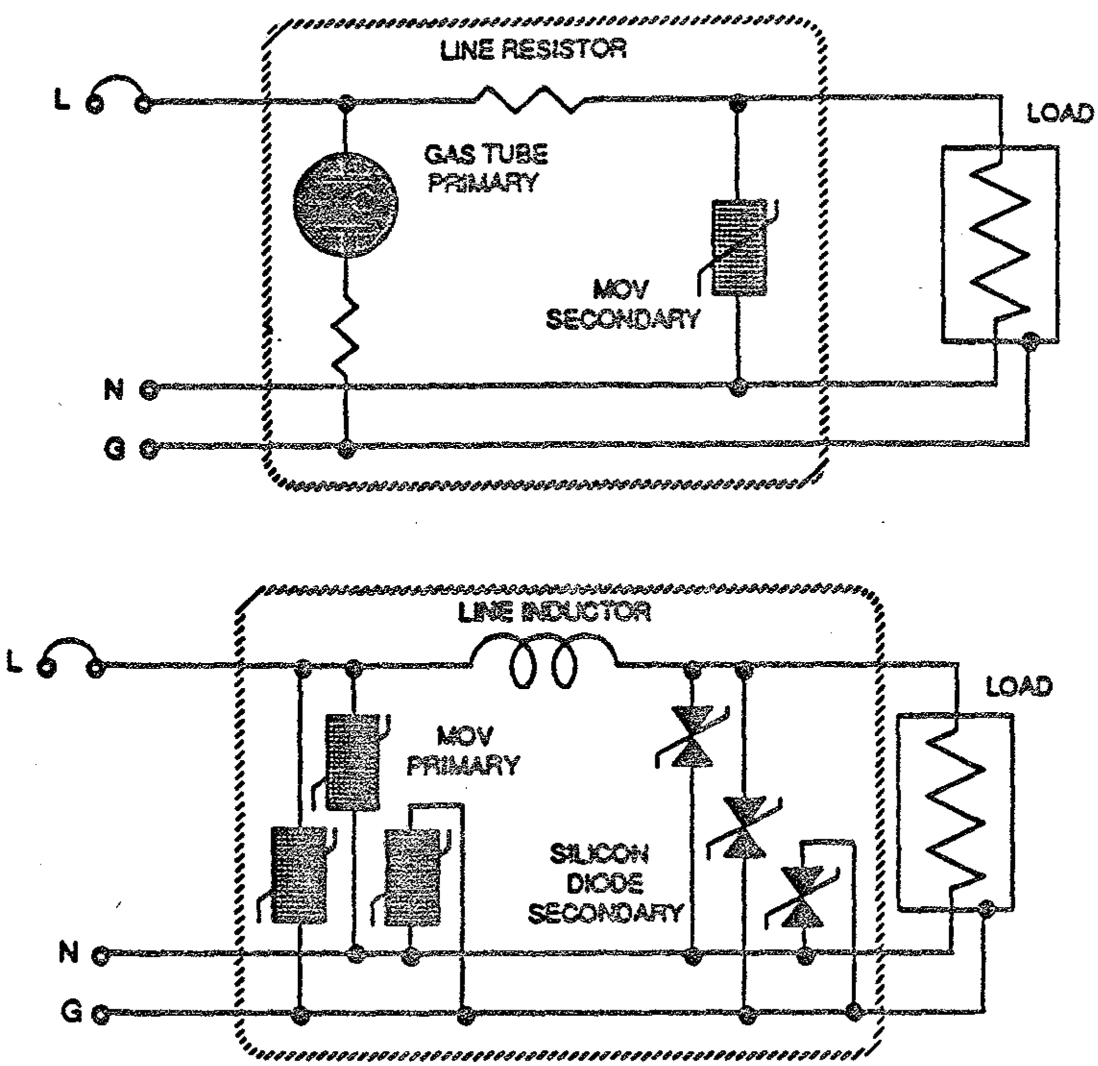


Figure 12. Two possible hybrid configurations employed in the construction of a transient surge suppressor. Top: Gas discharge tube and metal-oxide varistor. Bottom: Varistors and zener diodes configured to protect against surges appearing in all possible modes.

An electrical impulse is a traveling wave which typically progagates through the service wires in the order of 60 percent of light speed. Therefore, the components must be able to respond very quickly to the incident pulse. If a suppressor reacts slowly then a significant overvoltage can pass unimpeded through to the equipment supposedly being protected. The components which do react quickly are usually the ones with little power handling capability and for this reason the more effective suppressors are built with two or three cascaded stages. The stage nearest the load is for speed, to catch the leading edge of the surge. Preceeding stages react more slowly but dissipate the bulk of the surge energy as it passes through the suppressor. Each succeeding stage ideally triggers slightly later than the previous stage and diverts more energy. Coordination between stages therefore becomes essential in the hybrid suppressor.

An ideal surge suppressor would track the AC sinewave and clip transient spikes which are superimposed along any point of the wave. Most suppressors, however, utilize components which only operate on voltages exceeding the 170 volt sinewave peak. The actual clamping voltage varies due to differences in ratings of suppressors components and because clamping voltage is a function of the amount of current being diverted.

As an impulse voltage passes through the suppressor, the components will begin to conduct surge current as the voltage exceeds around 200 volts. But as the current being diverted to ground through the device increases, the clamping voltage rises. The final clamping voltage will be the peak value which is allowed to pass through the suppressor and is the voltage which will arrive at sensitive loads. This is sometimes called the Voltage Protection Level of the suppressor. The Clamping Factor of a component or an assembled device is the ratio of the peak clamping voltage to the initial voltage at which the device begins to conduct for a specified impulse. Ideally, surge suppressors would have a 1.0 clamping factor. They would clamp hard and fast on any voltage above the peak of the AC sinewave.

Surge Suppressor Components

Conventional surge suppressing components used in most surge suppressors include the following:

1. silicon zener diodes
2. gas discharge tubes
3. metal oxide varistors (MOV's)

Zener diodes are often used in the first stage of a surge suppressing device. They are positioned back-to-back between each line of a three wire system and react very quickly to an impinging transient pulse of either negative or positive polarity. This strategy provides initial protection to the load, but diodes by themselves have an inability to withstand surge currents for long periods without overheating and possibly failing. At least one company uses diodes exclusively in a power line surge protector, compensating for the diodes lack of energy handling capability by employing multiple diodes in the circuit.

Besides being extremely fast (zeners are available that can respond within picoseconds), they provide very tight clamping of the voltage spike.

Some special diodes developed for transient impulse protection, such as the Transzorb, have been very useful as surge suppressor components. They are extremely fast (less than one ns), have a low impedance, a relatively low cost and are reliable.

The oldest type of overvoltage suppression is the spark gap which basically consists of two closely spaced electrodes mounted such that a flashover will occur before a high voltage surge damages equipment. The flashover voltage is determined by the distance between the electrodes, the electrode geometry, and the rate-of-rise of the surge voltage. By encapsulating the electrodes in a vacuum-tight enclosure which contains gas at a certain pressure, the electrode spacing can be adjusted to regulate the flashover voltage of the gap. In this manner spark gaps can be constructed to have flashover levels compatible with low voltage residential systems. These devices are called gas discharge tubes and are sometimes used as the major power dissipating component in surge suppressors, although the MOV is by far the most popular component for this purpose.

Gas discharge tubes are crowbar devices. During operation they create a direct short circuit across the lines being protected, similar to placing a crowbar across the lines. Many argue that the zero voltage short circuit imposed on the system by a gas tube is a disturbance which may rival the original surge, emphasizing the fact that spark gaps are intrinsically slow in extinguishing the discharge. A substantial recovery transient may also be initiated at that time.

Power handling capability is the outstanding feature of a gas discharge tube. But their lack of speed is no secret, and their operation greatly depends on the slope of the incoming wavefront. For this reason that have fallen from popularity as microcomputer surge suppressor components.

The metal-oxide varistor is a bilateral device whose current-voltage characteristics approach the performance of a pair of avalanche (zener) diodes (Figure 13). It consists of a zinc oxide matrix and other metal oxide grains separated by grain boundaries. The boundaries block low voltage and conduct at 2-3 volts per boundary in a nonlinear fashion at high currents [13]. The surge energy capacity of a MOV is proportional to the volume of active material and the voltage breakdown level is proportional to thickness.

The MOV devices operate faster than spark gaps and provide lower voltage overshoot characteristics but they generally cannot handle as much current as spark-gaps. They have no problem with extinguishing or wearout (Figure 14) and are therefore attractive for many applications. Their main limitation, other than energy rating, is a relatively high capacitance ($\simeq 0.001\mu$F), which is not normally a problem in power circuits.

Zener diodes and MOV's are voltage clamping devices. "Clamping voltage" refers to the voltage level at which a suppressor will limit a surge. Clamping levels of most low voltage residential surge suppressors are typically around 220-300 V. A utility voltage of 120 V_{rms} reaches peak instantaneous amplitudes of $\pm$170 V during successive half-cycles of the AC waveform. Surge clamping devices are therefore designed to operate on voltages which exceed this normal AC peak value. A margin of safety between the normal AC peak level and surge suppressing device clamping levels is employed to allow for slow average rises in utility voltage. Were this safety factor not included it could cause extremely high current to flow through components

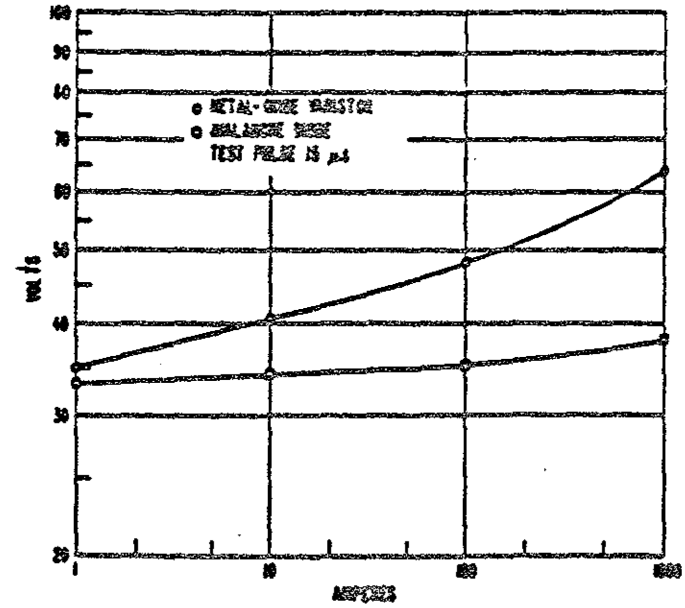


Figure 13. Voltage-current characteristics of the metal-oxide varistor along with that of the large-area avalanche diode out to 1000 amperes.

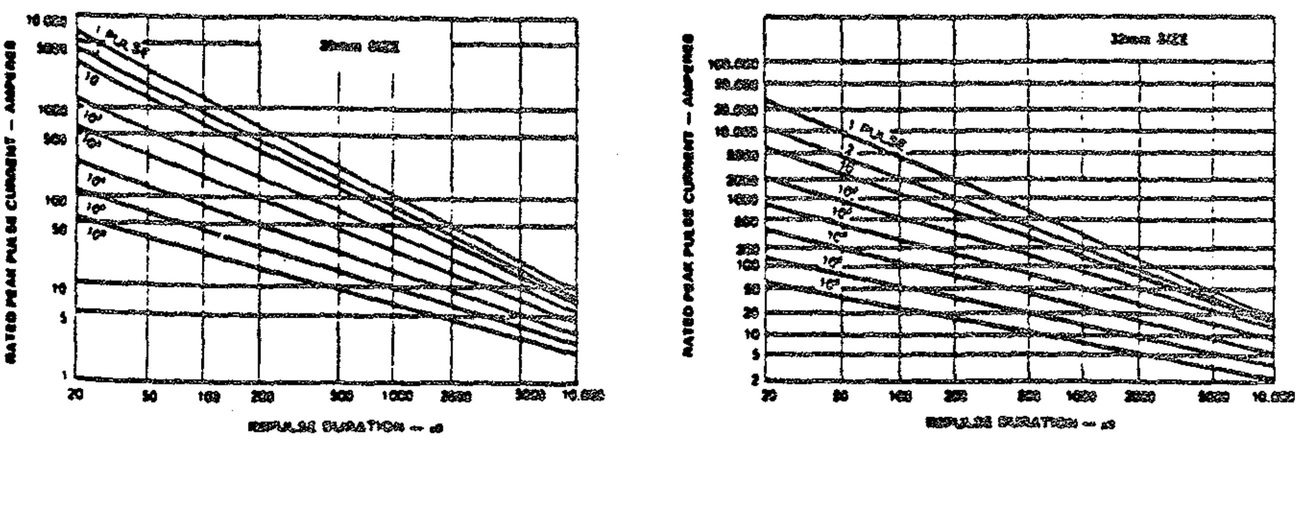


Figure 14. Pulse ratings of a 20mm varistor (left) and of a 32 mm varistor (right) [18].

as they attempt to clip off the sinewave peaks of an unusually high steady-state service voltage. Rapid overheating and failure of the devices would then occur.

Component Configuration

The surge suppressor in its most basic and inexpensive form consists of a single MOV connected across the line and neutral conductors within a plastic chassis having one, two, or four outlets. This configuration will limit normal mode transients according to the clamping level, speed and energy rating of the MOV used. It will not affect common mode transients.

Other suppressors, such as those previously observed in Fig. 12, may employ additional MOVs between line and ground and between neutral and ground to limit common mode transients. Probably the majority of low and mid-priced suppressors used only MOVs, although a few include passive filtering components. The more sophisticated suppressors combine MOVs, zener diodes and series resistors or inductors. Many have high frequency filters.

EMI/RFI Filters

EMI/RFI filters are included in many low-voltage surge suppressors contain low-pass filters to permit power at the line frequency to pass, while attenuating transient voltages having a higher frequency content.

Five computer surge suppressors with EMI/RFI filters were tested for normal mode filtering during this study and the resulting Bode plots of attenuation vs. frequency are included in Appendix C. The suppressors were provided for testing by local computer and electronics dealers.

The Bode plots show that few of the filters tested display significant attenuation below 100 kHz but are more effective in radio frequencies. Since transient frequencies are a wide band phenomena, from a few kHz to the MHz range, these tests indicate that many suppressors may be ineffective in attenuating line noise at the lower frequencies. This statement assumes that the suppressors tested here are representative of typical EMI/RFI filtering of most computer surge suppressors.

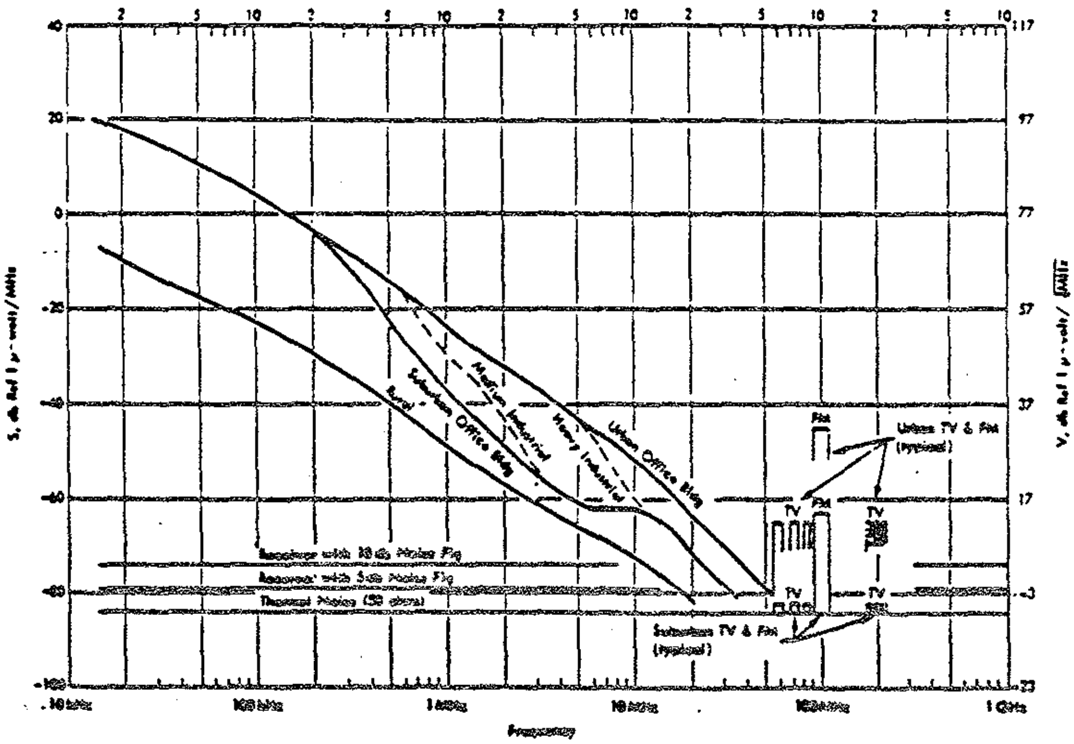


Fig. 15. Power line noise levels coupled into a 50 Ω receiver [39].

In a study of power line noise created by DC and universal motors [38], voltage and current spectra of the following appliances were analyzed to 100 kHz: A small blender, a large blender, a vacuum cleaner, a reversible drill, a sewing machine and an electric sander. The motors of these devices operate from 3,500 to 10,000 rpm at full speed. The spectra showed that the fundamental noise frequency was less than 10 kHz for each motor tested. In some cases distinct harmonics of the fundamental occured out to 100 kHz at lower amplitudes.

Fig. 15 shows the average noise levels coupled into a 50 Ω receiver for rural and urban electrical environments. The difference between rural and urban office levels is nearly 30 dB. The 20 dB/decade decrease in noise results from lower generation levels and from increased attenuation at higher frequencies. It was reported in [39] that electrical noise from common household appliances did not add significantly to background levels. The worst offenders were a vacuum cleaner and a light dimmer, which added less than 3 dB to existing levels and very little of this noise coupled across the distribution transformer.

Another type of suppressor, not obtained for testing in this study, is perhaps better suited for attenuating transients having predominantly low-frequency content. "Sine wave tracking" devices are indistinguishable from typical surge suppressors, but essentially consist of high-quality filters, although varistors and avalanche diodes may also be incorporated into the design.

Standard Tests for Evaluating Surge Suppression Performance

The most widely applied test for evaluating the effectiveness of microcomputer surge suppressors is the IEEE 587-1980, *IEEE Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits.* Recently republished as IEEE C62.45-1987 [98], this document suggests the impulse waveshapes, magnitudes, and current delivering capabilities of test surges appropriate for determining the impulse withstanding capability of low voltage electrical equipment and the surge protection levels of various types of suppressing devices. A similar document, Underwriters Laboratories UL 1449, *Transient Voltage Surge Suppressors* [99], specifies the same waveshapes as are recommended in the IEEE testing guidelines. UL 1449 contains the basic requirements for indoor surge suppression products designed for repeated limiting of transient voltage surges on 50 and 60 Hz power circuits. It should be noted that the IEEE 587 is a *guideline* for surge testing equipment operating at service voltages, whereas UL 1449 is a Standard for products covered by Underwriters Laboratories Inc.

Scope of Impulse Testing for Rural Alaska

The testing of the surge suppressing capabilities of all power conditioning equipment was conducted utilizing impulse waveshapes as suggested in the IEEE 587-1980 guidelines. The IEEE 587 recommended test impulses can be observed in Fig. 16. The magnitude of test impulses was varied to include test surges of less than 3.0 kV in consideration of the results of village power system monitoring.

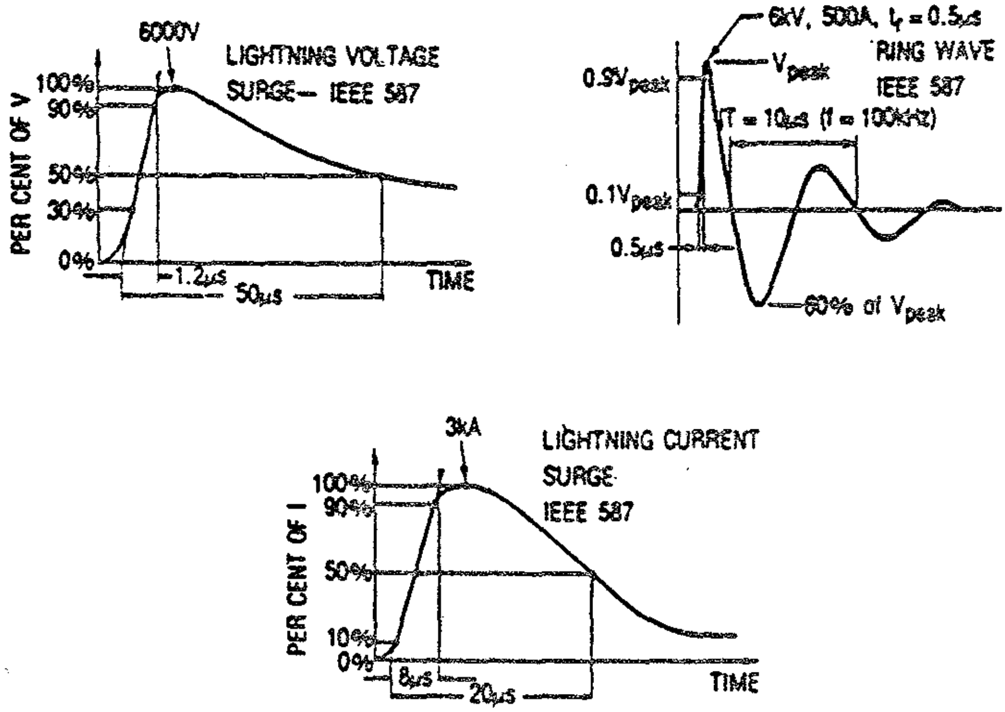


Figure 16. IEEE 587 test impulses. Top left: 1.2x50μs unipolar voltage impulse. Top right: 0.5μs, 100 kHz ringwave. Bottom: 8x20μs current surge corresponding to the 1.2x50μs voltage surge.

Each device tested was subjected to the full 6.0 kV levels of the IEEE 587-1980 guidelines if failure of the device did not occur at lower voltage levels. Testing was therefore intended to provide information about the ability of protective devices to attenuate severe transients as well as the "real world" disturbances recorded in a vast, sparsely populated region having an isokeraunic level of less than 5 and very few industrial loads. The 500 A, 100 kHz category B ringwave as defined in the IEEE 587-1980 was not applied during testing of any device.

Impulse Test Equipment

Surge tests were conducted using a KeyTek Model 587 surge generator on lease from Consulting Engineers.

Consulting Engineers
21386 Sail Bay Drive
Cassopolis, Michigan 49031

Surge monitoring was implemented with a Hewlett Packard 54201A Digitizing Oscilloscope.

Test Procedure

The following test surges were applied to all power conditioning devices listed in this report. Each oscillatory Ring Wave, whether applied in the transverse or common mode, was applied with the KeyTek 587 surge wave selector in the 200 Amp position. All unipolar 1.2 x 50μs test waves were applied with the 587 surge wave selector in the 500 Amp position.

1. Transverse mode: Ringwaves applied to equipment under test with varying impulse amplitudes from 100 V to 1.0 kV in increments of 100 volts.

2. Common mode: Ringwaves applied to equipment under test with varying impulse amplitudes from 100 V to 1.0 kV in increments of 100 volts.

3. Transverse mode: Ringwaves applied to equipment under test with varying amplitudes of 2.0 kV to 6.0 kV in increments of 1.0 kV.

4. Common mode: Ringwaves applied to equipment under test with varying amplitudes of 2.0 kV to 6.0 kV in increments of 1.0 kV.

5. Transverse mode: 1.2 x 50μs unipolar impulse applied to equipment under test with varying impulse amplitudes from 100 V to 1.0 kV in increments of 100 volts.

6. Common mode: 1.2 x 50μs unipolar impulse applied to equipment under test with varying impulse amplitudes from 100 V to 1.0 kV in increments of 100 volts.

7. Transverse mode: 1.2 x 50μs unipolar impulse applied to equipment under test with varying amplitudes of 2.0 kV to 6.0 kV in increments of 1.0 kV.

8. Common mode: 1.2 x 50μs unipolar impulse applied to equipment under test with varying amplitudes of 2.0 kV to 6.0 kV in increments of 1.0 kV.

All devices tested were loaded with a resistive load equal to one-half the rating of the device during the tests. The majority of equipment selected for testing were rated at 500 volt-amperes, therefore the loading for these conditioners was 250 watts. Indoor impulse suppressors were also loaded at 250 watts, though most were rated to support loads in excess of 1.5 kW.

Impulse Testing Measurements

Applied surges to each Equipment Under Test (EUT) were adjusted in magnitude from 0 to 6.0 kV by a rotary set voltage control and digital read-out located on the faceplace of the KeyTek 587 surge generator. Monitoring of the surges downstream from each EUT (on the protected side) was accomplished using the internal 200:1 attenuator of the KeyTek 587 and the HP 54201A oscilloscope.

For each type and magnitude of test impulse applied to an EUT the output of the EUT was monitored line-to-neutral, line-to-ground, and neutral-to-ground. For example, if a particular EUT is being tested at 2.0 kV with a 1.2 x 50μs impulse applied in the common mode then the impulse must be applied three times in order to make the three measurements. At the conclusion of the test sequence listed above, the EUT will have been subjected to a minimum of twelve impulses at the 2.0 kV level. The equipment under test will have received two impulse waveshapes, each applied in both the common and transverse modes and each mode applied three times for observation.

Each equipment under test was impulsed from 100 V to 1.0 kV in 100 volt increments and from 1.0 kV to 6.0 kV in 1.0 kV increments. Considering all possible modes of incident impulses and measurements, each EUT was subjected to 168 impulse voltages except where the testing of certain devices did not include the higher voltages due to high voltage limitations specified by manufacturers.

Test Results

Varistor-based suppressors generally exhibited good performance in suppressing impulse voltages exceeding 150 V and superimposed on the peak of the positive half-cycle of the 60 Hz utility voltage (Appendix A). Impulses of negative polarity or impulses of either polarity occurring at positions other than the AC half-cycle peaks were suppressed in proportion to the degree in which the impulse plus instantaneous AC value exceeds the conduction threshold voltage of varistors.

Suppressors were less effective when the applied impulses were in the range of those measured in rural Alaska in [3]. Impulses of less than 150 V passed through suppressors with little attenuation unless series elements were present. Figures 17 and 18 compare the impulse protection levels, at 200 V and 6.0 kV, provided by surge suppressors, voltage regulators, power conditioners, uninterruptible power systems and isolation transformers which were tested during this study.

Figure 17 illustrates the wide range of effectiveness of the various devices in attenuating a 200 V normal mode (line-to-line) impulse voltage. This impulse represents a realistic disturbance to be expected in both rural and urban communities caused by either local loads or utility switching. Suppressors which tested poorly at the 200 V level performed adequately in tests at the IEEE 587 6.0 kV test levels for normal mode disturbances (Fig. 18).

Those suppressors tested which had provisions for removing the suppressor chassis and inspecting component configuration were found to be varistor-based devices and it is suspected that all suppressors tested utilized varistors as the major surge current diverting mechanism. Approximately half of the surge suppressors tested were constructed such that their circuit boards could not be inspected without damaging either the chassis or the internal circuit board and components.

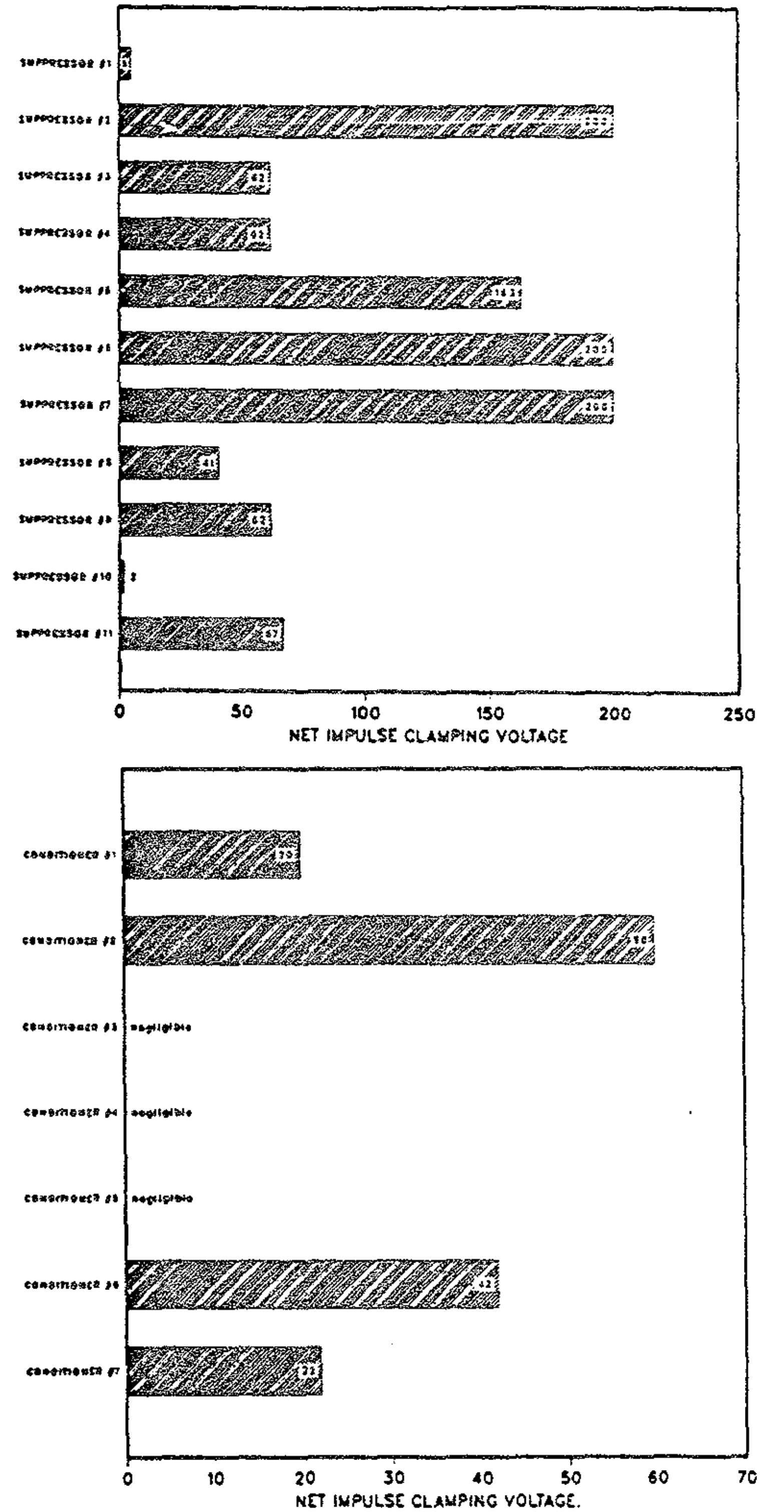


Figure 17. Comparison of line-to-neutral surge clamping response of surge suppressors (top) and power conditioners/UPS (bottom) to a 200 V normal mode impulse.

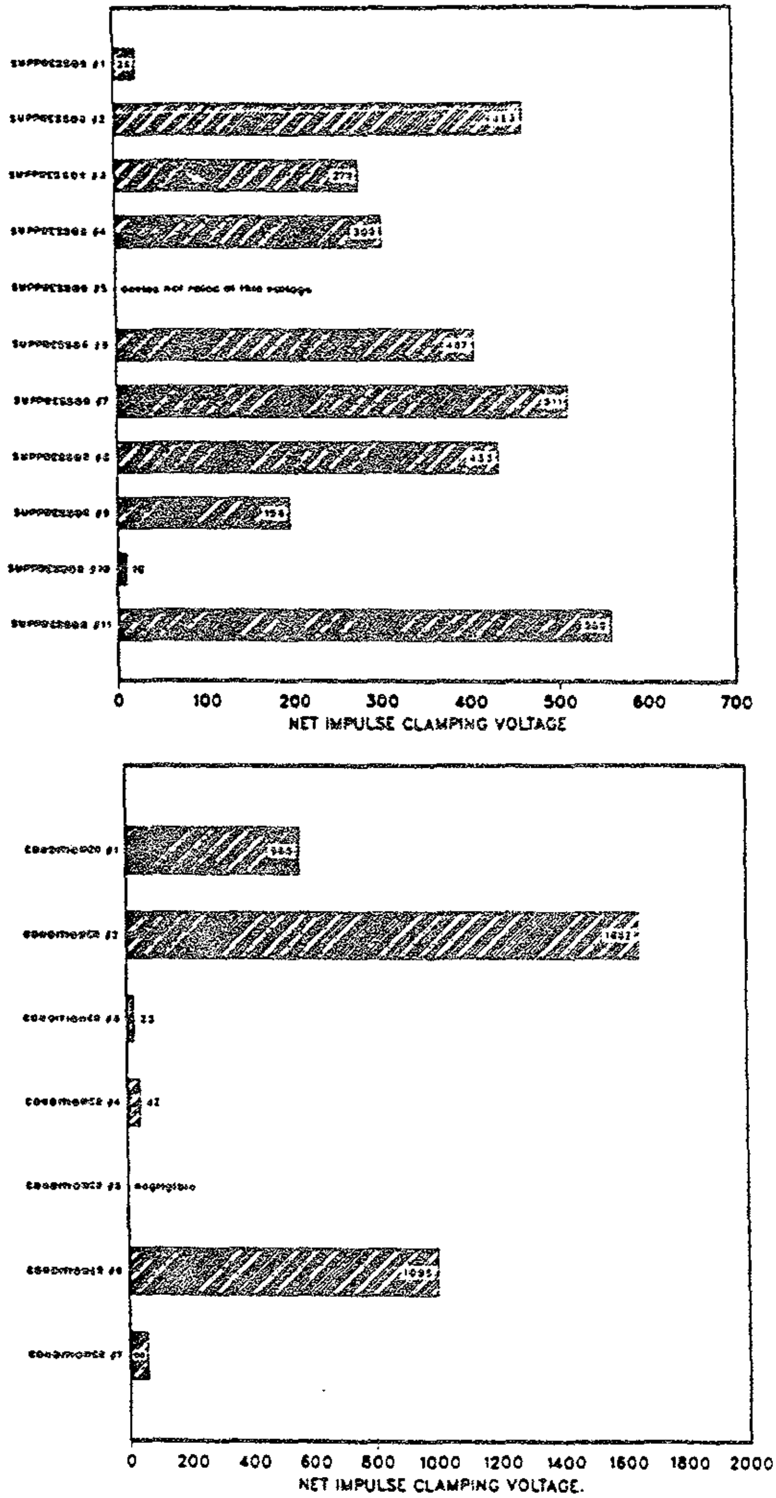


Figure 18. Comparison of line-to-neutral surge clamping response of surge suppressors (top) and power conditioners/UPS (bottom) to the IEEE cat. A 6.0 kV normal mode ringwave.

The suppressors tested varied in cost from $20 to $100. Three suppressors were closely grouped in price at the high end of this range. Of the three, two exhibited the lowest impulse clamping level, therefore the best performance, of the surge suppressors tested (Appendix A, Suppressor #1 and Suppressor #10). The third $100 suppressor (#11) provided surge clamping comparable to that of the lower priced suppressors and the device suffered component damage during high-level voltage tests.

Most of the eleven surge suppressors were priced between $20 and $40 and consisted of either a single MOV connected between line and neutral (typical $20 suppressor) or three MOVs connected in the three modes: line-to-neutral, line-to-ground, and neutral-to-ground. One inexpensive suppressor included a series coil. Two had EMI/RFI filters in the form of a single capacitor connected between line and neutral. dvips 4chap

UNINTERRUPTIBLE POWER SUPPLIES

The True UPS

Uninterruptible power supplies (UPS) are considered to be the ultimate protection from powerline disturbances. A true uninterruptible power supply is designed to provide total isolation from the powerline for critical loads. In its basic form, a UPS consists of a battery power supply, battery charging circuitry and a solid-state static power inverter. Power to critical loads is continuously supplied by the inverter which electronically synthesizes a 60 Hz waveform of specified voltage. The inverter draws its energy needs directly from the battery, therefore the AC powerline functions only for battery charging.

This "true" UPS operates with the inverter always on. The load is never directly connected to the commercial power supply except in the event of inverter failure or unit maintenance, in which case a transfer switch is available to transfer the load directly to the commercial supply, either manually or automatically, should the inverter become overloaded or fail. When power is being supplied by the inverter the critical or sensitive load is protected from all powerline disturbances because it is completely isolated from utility service.

Often, one encounters such terms as "reverse transfer UPS", "on-line UPS", or "make-before-break UPS". These terms describe a true uninterruptible power supply. A true UPS will provide power to a critical load without interruption. In the event of a power system blackout the battery charging circuitry is disabled and the system can only continue to sustain power to the loads according to the capacity of the battery installed with the system. When the commercial supply has resumed, the battery charger is again in service and will restore the battery energy used during the outage. The battery backup times for different load levels is normally included in the equipment specifications.

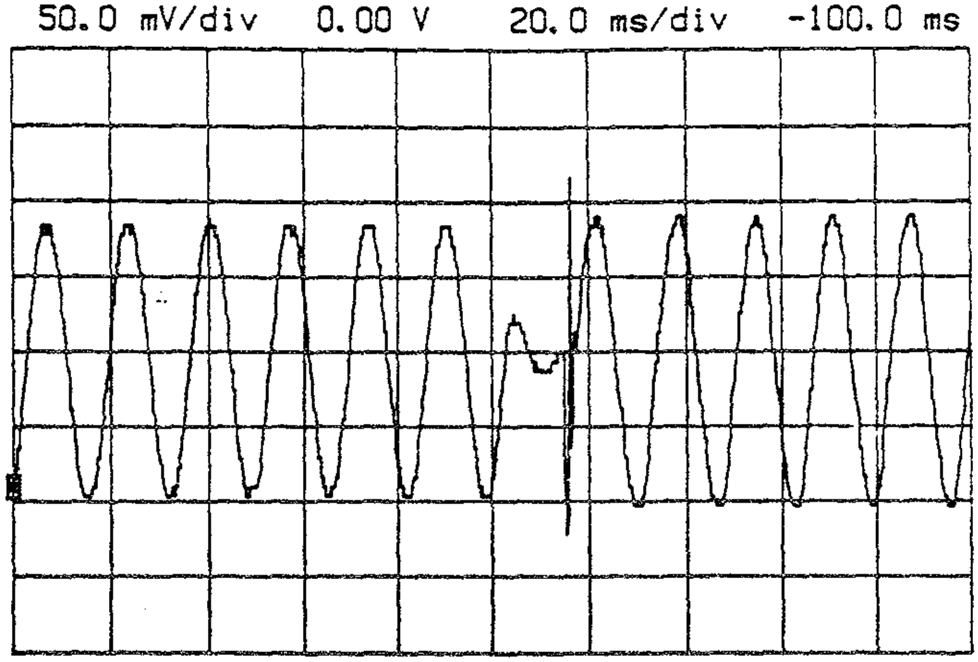


Figure 19. Switching delay of a sinewave standby power system. The Datashield AT-500 inverter picks up the load within 12 ms of a powerline failure.

Standby Power Systems and A New Generation of UPS

Another popular type of power supply, especially for microcomputer applications, is the large group of inverter-based power supplies formerly called Standby Power Systems. Standby Power Systems (SPS) are essentially the same as a true UPS except that the inverter is only activated in the event of a powerline failure. Early SPS models utilized a manual switch to turn on the inverter in the event of a blackout. More recently, SPS manufacturers employ a solid-state or mechanical relay which switches on inverter circuitry when utility voltage falls below a preset level, normally between 102 and 108 volts.

Oscillograms of the instant of switching for three Standby Power Systems are shown in Figures 19 through 22. In each case, the activation of the SPS inverter is preceeded by a loss of power line voltage for a period of approximately one-half cycle. These oscillograms were obtained using the "plug pull" test. During the test,

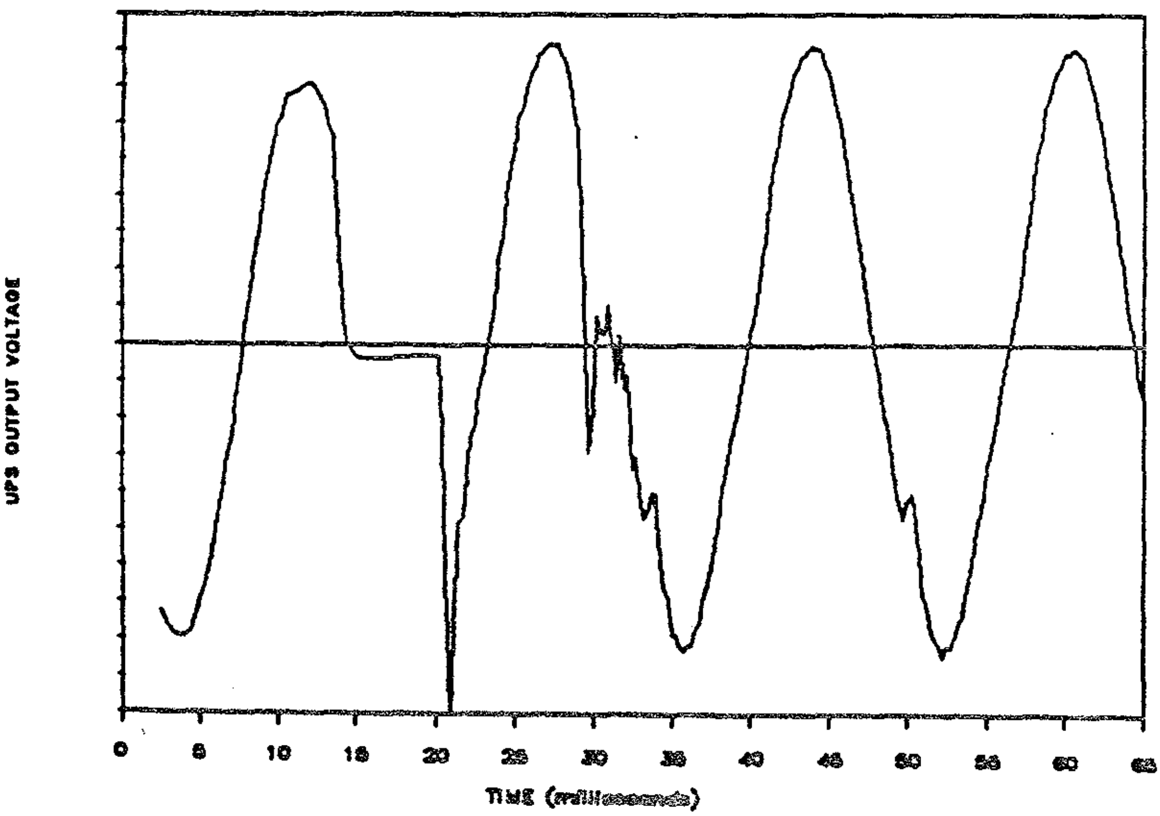


Figure 20. Switching delay of a 500 VA Topaz Standby Power System. The delay time for this device is approximately 5 milliseconds.

the SPS power cord was pulled from the duplex wall receptacle while monitoring the SPS output voltage.

This new generation of uninterruptible power supply has the ability to sense voltage problems very quickly and transfer to backup power in a few milliseconds. The rapid transfer of power sources virtually eliminates the need for a true UPS because loads will continue to operate during the brief power interruption. Under normal conditions, the load is powered from the AC service supply. SPS control circuitry continuously monitors input voltage and initiates inverter operation when the utility supply voltage drops below or rises above the specified level. This approach puts the inverter into service only under low-voltage or blackout conditions.

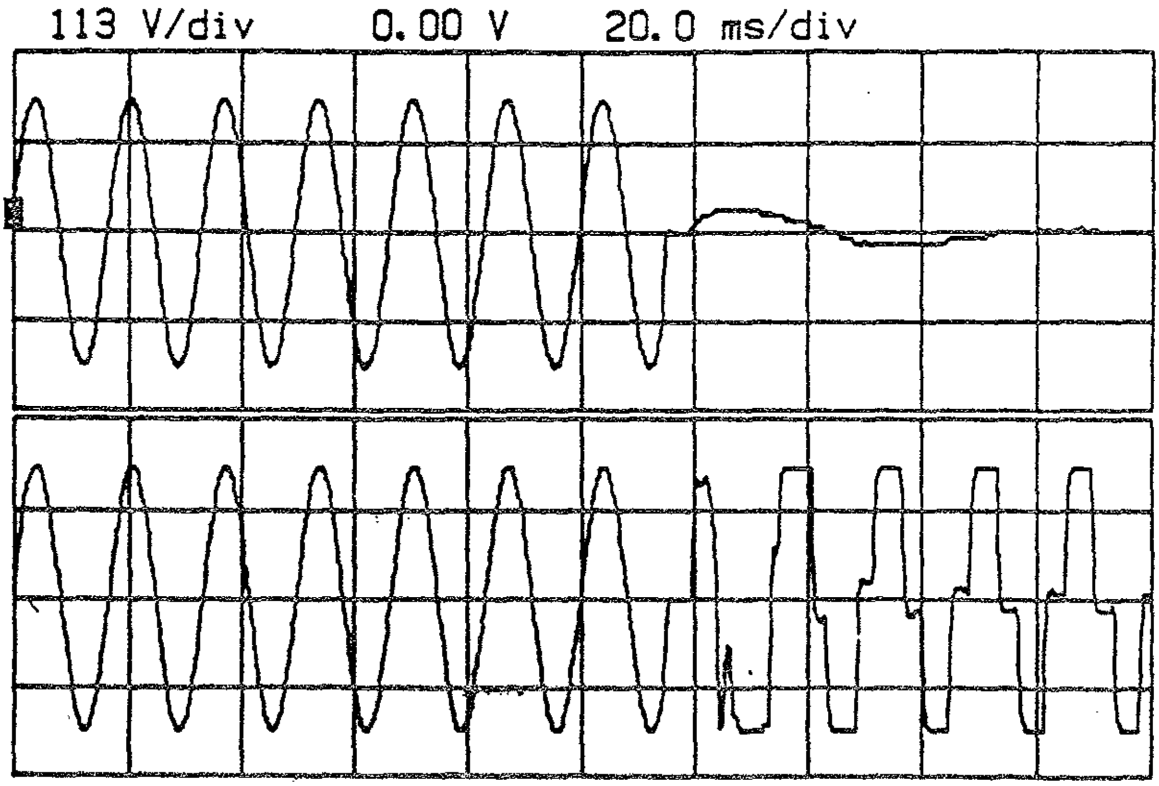


Figure 21. American Power Conversion's 450 AT$^+$ UPS switching on inverter in response to a blackout. The switching time here is less than three milliseconds.

Most SPS units provide limited or no protection from transient disturbances while the commercial service is operating within the input voltage envelope because the load is directly connected to the AC service through the SPS. Voltage sags, surges, impulses and frequency deviations pass unhindered through the SPS during normal conditions. Many standby power systems, however, include surge clamping varistors (MOVs) at the input to suppress the higher impulse voltages.

Several SPS manufacturers employ ferroresonant transformers at the SPS output to filter and regulate output voltage. A ferroresonant transformer will also provide waveshaping to the output of a squarewave or modified sinewave inverter producing a reasonably clean sinusoidal output. Ferroresonant transformers can also reduce the apparent transfer time of an SPS at the instant of a power failure by releasing the stored energy of the resonating transformer secondary. Advanced sinewave inverters may employ forced thyristor commutation techniques to achieve a sinusoidal output.

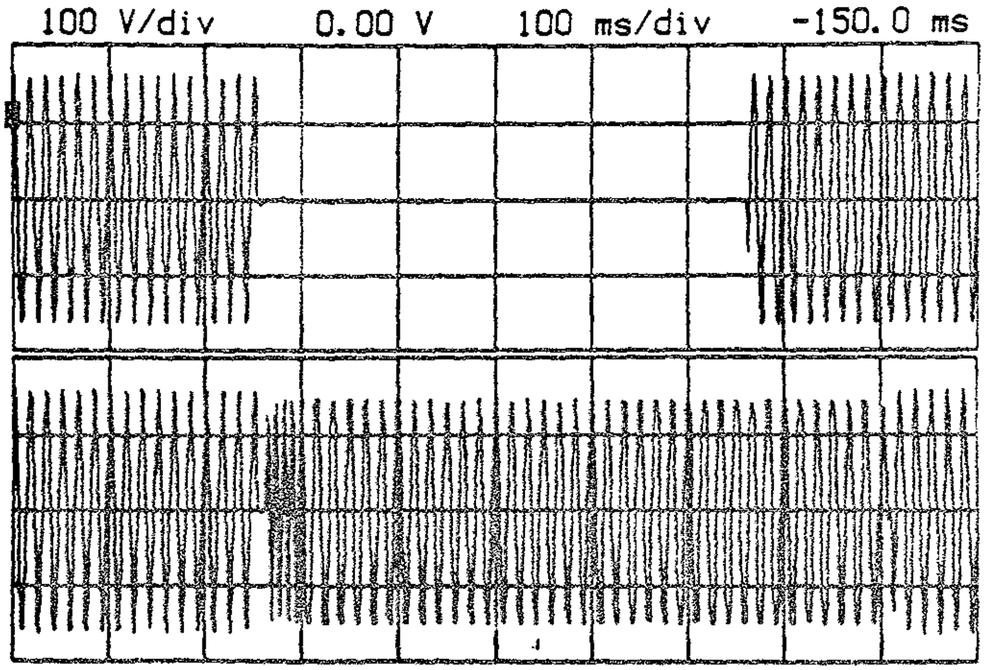


Figure 22. DataSaver 200 switching to inverter following a blackout. This inverter switches in 8 milliseconds.

SPS systems do not provide uninterruptible power in the strict sense because the load will experience a momentary interruption in the supply voltage before the SPS has sensed the voltage problem and transferred the load to the inverter. Nevertheless, the trend among SPS manufacturers is to christen their products as uninterruptible. SPS manufacturers specify extremely fast transfer times following an input power failure. Some systems will have the inverter running and switched to the load typically within a few milliseconds after the input voltage ranges outside the envelope of tolerable voltage levels. A personal computer can generally ride through power interruptions of 8 milliseconds in duration, depending on the DC power supply of the machine. This constitutes the basis of the justification in labeling the SPS as uninterruptible. In all likelihood a computer or other electronic load will not be affected by the brief power failure.

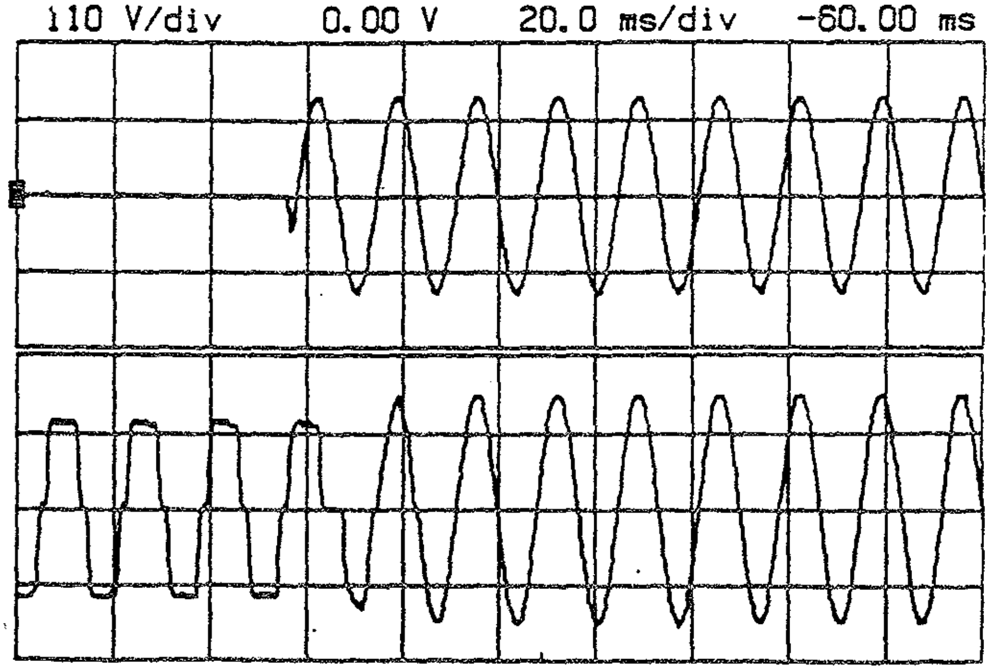


Figure 23. Synchronization of the DataSaver 200 to the power line after normal voltage has resumed.

Today the SPS terminology, although still used to some extent, is rapidly waning. Nearly all inverter-based backup power supplies are now called UPS and it is the task of the buyer to sort them out and to determine their compatibility with individual loads.

The UPS buyer should be aware that transfer times specified in sales literature are often misleading. The actual duration of an interruption seen by a load downstream from a UPS (formerly SPS) at the instant of a blackout is the sum of two individual events: (1) the time required for control circuitry to sense the power failure plus (2) the time required for a solid-state or a mechanical relay to transfer the load to the inverter. The specified transfer time of a UPS may only represent the speed of the switch and exclude the sensing time, or it may represent a "best case" situation (sensing speed for a particular outage depends on the exact point in the AC cycle at which a power failure begins).

The transfer time specified for a unit may often be qualified as "typical". Independent tests of UPS transfer speeds [64] show that many switching UPSs present a longer power interruption to a load than is apparent from sales literature. When choosing power conditioning equipment for critical loads it is important to remember that it is the worst case, not the best or the average, which will most likely cause problems.

UPS Backup Time

Many uninterruptible power systems of less than 5 kVA rating incorporate batteries which are housed inside the UPS cabinet. They are designed to provide power to critical loads for less than fifteen minutes. With few exceptions, small UPS systems do not include provisions for adding external batteries to increase their backup capability. Battery backup time for UPS systems should be carefully considered in rural power systems where essential loads are involved. Critical loads in rural Alaskan power systems should have, as a minimum, several hours of autonomy from the system.

UPS Testing

Two uninterruptible power supplies, both of the standby type, were tested for response to various voltage disturbances as well as for rote switching speed. The models tested are listed below.

Manufacturer	Model
American Power Conversion	450 AT+
Cuesta Systems Corporation	DataSaver 200

The basis for choosing these particular units for testing was that they are representative of the many microcomputer-sized UPS systems which are commercially available. The manufacturer's specifications are listed in Table 10. Both utilize inverters which deliver a nominal 120 V modified square wave output. Both also specify typical transfer times when switching from utility supply to inverter and both are competitively priced.

UPS Specifications

	DataSaver 200	AT 450+
Power Rating (watts)	200	300
Backup Time (minutes, typical at full power)	5	7
Line Input Voltage (RMS)	120	120
Line Input Frequency (Hz)	60	60
Low Voltage Trip Point	103 V_{ac}	102 V_{ac}
Output Voltage (RMS)	102-132	117 V_{ac} ±5%
Output Frequency (Hz)	60 ±0.1%	60 ±0.6%
Transfer Time (ms)	2-8	1-3
Surge Suppression	198 Volts	0.7% of IEEE Cat. A
Size (HxWxL in Inches)	4x6x9	6.6x4.7x14.2
Weight (Pounds)	14	25
List Price	$495	$595

Table 10. UPS Specifications for Rural Power Quality tests.

The DataSaver specifies a 2-8 millisecond line to UPS transfer time which was verified in laboratory tests. The 450 AT+ specifies a maximum transfer time of 3 milliseconds. Measured transfer times for the 450 AT+ did not exceed that value. Both units were able to keep a PC's Limited 286 computer running without interruption when their line cords were pulled from the receptacle. The corresponding waveforms were previously illustrated in Figures 21 and 22.

The DataSaver is one of the few small UPS units which has provisions for the adding external battery capacity. It's internal gel-cel battery is rated for 5 minutes of standby power at full rated output. The 450 AT+ has a noticeably larger internal battery and specifies 9 minutes of standby power under a 300 watt load. Neither of these units would therefore be appropriate for critical loads in rural Alaska unless additional battery capacity was included.

Although the DataSaver 200 has input jacks for installing auxiliary external 12 volt batteries, manufacturer representatives advised that the battery charging circuitry in the unit may not be able to recharge external lead-acid batteries from a

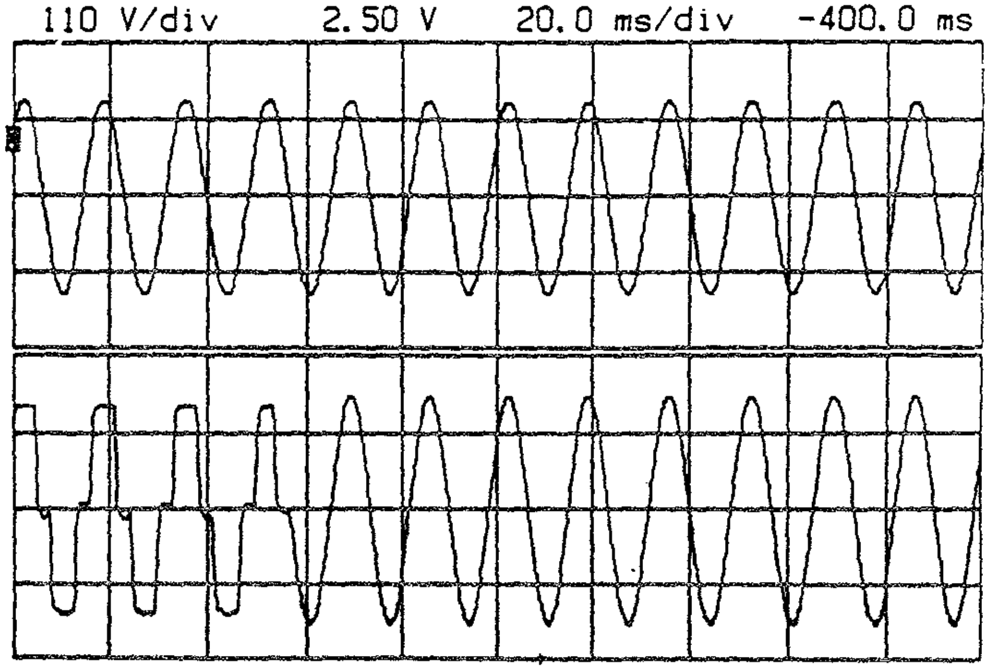


Figure 24. Synchronization of the 450 AT$^+$ to the power line after normal voltage has resumed following a power system outage.

deeply discharged condition. It would therefore appear that in order to make small UPS units effective for longer power outages, both additional battery capacity and external charging may need to be incorporated into the UPS system either by the user or by the manufacturer on special request.

UPS responses to sag and surge voltages and to the 1/2 cycle voltage dropout test are shown in Appendix D. Both UPS responded to the 1/2 cycle dropout by switching on the inverter quickly enough to meet the requirements of most critical loads. The American Power Conversion 450 AT$^+$ was subjected to the same sequence of impulse tests as were the computer surge suppressors, power conditioners, ferroresonant transformers and the Topaz high-isolation transformer (Appendix B). Varistor-based surge suppression circuits have been incorporated into both UPS systems tested, although the DataSaver 200 was not subjected to impulse testing. The effect of including varistors in a UPS is similar to connecting a UPS downstream from a computer surge suppressor, and the relative effectiveness of the UPS surge suppression components can be seen by comparing the response of eleven computer surge suppressors (Appendix A) with the suppression levels recorded for the 450 AT^+ in Appendix B.

The 450 AT^+ suppressed ringwaves of varying amplitude occurring in the normal mode as well as nearly all computer surge suppressors tested. Since these impulse disturbances constitute the majority of those expected to occur in Alaska it can be concluded that this particular UPS should provide adequate surge suppression without the need for installing a discrete suppression device. The 450 AT^+ was less effective in suppressing common mode ringwaves as well as unipolar impulses in both modes.

CHAPTER 6

COMPUTERS AND POWER PROBLEMS

Introduction

Critical loads are electrical or electronic devices which are providing services considered to be essential or devices which are inherently sensitive to subtle voltage abnormalities. Computers are often considered to be critical loads by the high priority nature of data being processed. The power conditioning industry commonly describes computers as sensitive, although there are few data supporting that claim on a power quality basis. Most computer equipment can withstand voltage fluctuations of +6% and -15% and their power supplies provide good filtering of line noise signals.

Computer systems are prone to crash following voltage sags below 80% of nominal voltage for more than one cycle in duration and, like most electronic equipment, are susceptible to catastrophic damage by lightning-induced high voltage impulses. It is unlikely that the impulse voltages measured in rural Alaska will cause failure to computers at higher rates than other electronic equipment. However, repeated exposure to low-level impulses may shorten the lifetime of power supply components. Some computer networks are also subject to data pollution by circulating ground currents manifesting as common mode voltages which can raise logic ground levels of the computers and peripherals within the network.

The Computer Tolerance Envelope

Few quantitative data have been offered which characterize the actual transient susceptibility of computer equipment. The most widely cited reference to computer power requirements is the Computer Tolerance Envelope (Fig. 25) which was submitted in the well known paper written by a U.S. Naval engineer in 1979 [6]. The intent of the Computer Tolerance Envelope was to recommend power tolerance limits to be achieved by computer system designers. The recommendations were based on a combination of Navy electronic equipment susceptibility test results and Navy

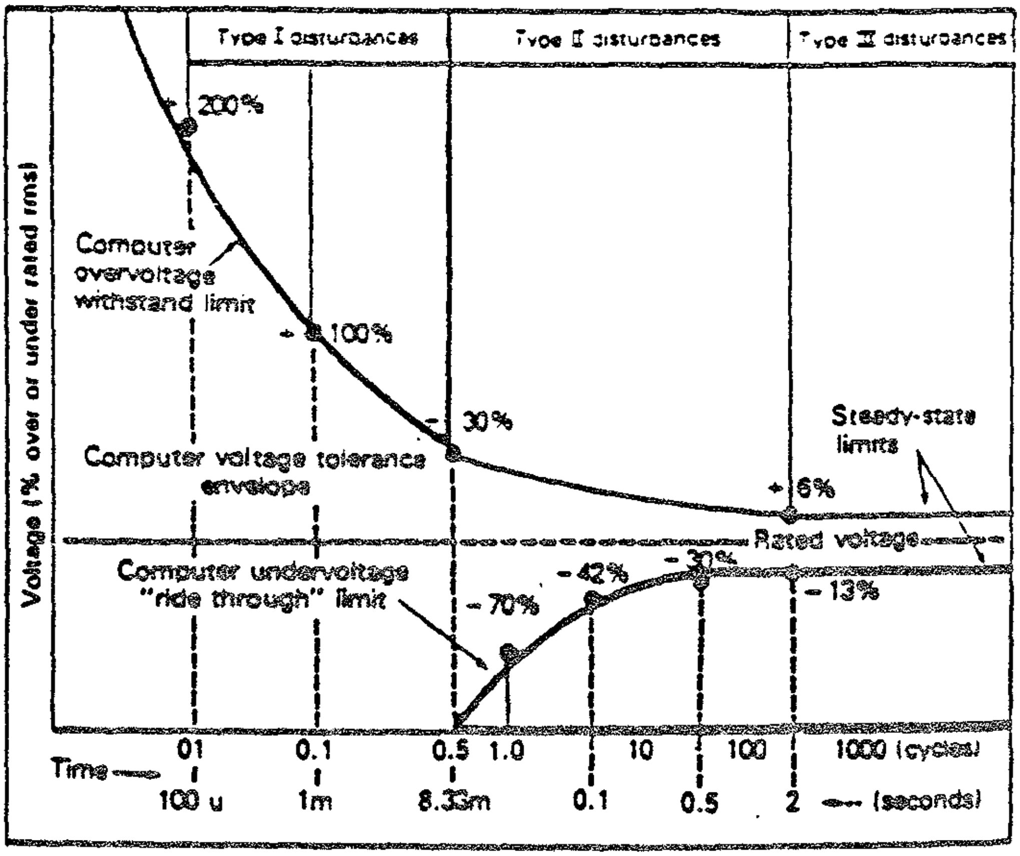


Fig. 25. Computer Tolerance Envelope.

computer power studies which compared computer failures with voltage monitoring results.

The Computer Tolerance Envelope classifies line disturbances based on duration; Type I disturbances lasting less than 1/2 cycle of the 60 Hz waveform, Type II disturbances lasting between 1/2 cycle and 2 seconds, and Type III disturbances representing deviations in steady-state voltage level. These classic definitions continue to be widely used as references in line-monitoring studies. The 1/2 cycle ridethrough specifications of contemporary power conditioning equipment is based on the guidelines of the Computer Tolerance Envelope. The input range of power quality specified by computer manufacturers (Table 11) is not inconsistent with the recommendations in [6].

Ridethrough

Ridethrough refers to the ability of an electronic device to withstand short-term power failures without affecting device operation or, in the case of computers, interruption of data processing. The device is said to *ridethrough* the line failures. Ridethrough is achieved through energy storage and release by passive power supply components, mostly filtering capacitors, and is specified in terms of milliseconds. Should the AC input voltage drop to zero for a quarter-cycle (approximately 4 milliseconds) to the power input terminals of a device which claims to have ridethrough capability of 5 milliseconds then we would expect the device to function properly in spite of the power interruption.

Unfortunately, the manufacturers of electronic equipment do not normally provide ridethrough information about their products. The ridethrough ability of computers depends on the particular power supply which has been incorporated into the system and, since computer buyers are not given this information at the time of purchase, the ridethrough expectation of computers is generally taken from the Computer Tolerance Envelope as 8 milliseconds. This is this value which manufacturers of power conditioning equipment try to meet by incorporating sufficient capacitance in the conditioner to ridethrough a complete power failure for a half-cycle. Most computer power supplies will shut down following a complete loss of voltage of more than one cycle.

Audio power amplifiers are typically loaded with large capacitors and consequently possess extraordinary ridethrough capability. The intentions of the audio industry are to provide continuity of supply and increased dynamic power by releasing stored energy in the capacitors when either supply line voltage fails or musical peaks require reserve power. It is not uncommon for a high-fidelity audio system to continue playing for several seconds following a complete loss of line voltage.

Input Range of Computer Power

Parameter[a]	Range or Maximum
1) Voltage Regulation, steady state	+6 to -13 percent
2) Voltage disturbances	
Momentary undervoltage	-25 to -30 percent for less than 0.5 s with -100 percent acceptable for 4-20 ms
Transient overvoltage	+150-200 percent for less than 0.2 ms
3) Voltage harmonic distortion[b]	3-5 percent (with linear load)
4) Noise	No standard
5) Frequency variation	60 Hz ±0.5 Hz to ±1 Hz
6) Frequency rate of change	1 Hz/s (slew rate)
7) 3ϕ phase voltage unbalance[c]	2.5 to 5 percent
8) 3ϕ Load unbalance[d]	2-20 percent max. for any one phase
9) Power factor	0.8-0.9
10) Load demand	0.75-0.85 (of connected load)

[a] Parameters 1), 2), 5), and 6) depend on the power source while parameters 3), 4), and 7) are the product of an interaction of source and load and parameters 8), 9), and 10) depend on the computer load alone.

[b] Computed as the sum of all harmonic voltages added vectorially.

[c] Computed as follows:

$$\text{percent phase voltage unbalance} = \frac{3(V_{max} - V_{min})}{V_a + V_b + V_c} \times 100.$$

[d] Computed as the difference from average single-phase load.

Table 11. Typical range of input power quality and load parameters of major computer manufacturers [38].

Component Degradation and Equipment Failure

The problem of high voltage transients can cause failure of semiconductor components in computer power supplies and other solid-state electronic systems if the transient contains sufficient energy, a function of magnitude and duration. Although the damage may not be as obvious as scorched components or circuit boards, it can cause random failures during normal operation of equipment. The effects of voltage transients on semiconductor devices are therefore said to be either degrading or catastrophic.

Device degradation refers to local breakdown at points in the *pn* junction due to low-energy transients which precipitates deterioration of parameters such as leakage current and which leads to the eventual failure of the component. Catastrophic failure implies immediate breakdown of a device upon the incidence of the transient. If the spikes are not suppressed, or inadequately suppressed and have a high magnitude, they may cause component degradation or catastrophic breakdown of a transistor because of overheating or breakdown of the junction. Although the amount of energy in a spike may be small, it was reported in [70] that any prolonged repetition of such spikes tends to cause an internal short between the emitter and collector of a transistor.

Computer Power Supplies

Although the scope of this project does not specifically include testing of the impulse withstanding capabilities of various loads, it is nevertheless appropriate to discuss briefly the inherent noise filtering provided by typical computer power supplies.

Almost every electronic device uses some type of power supply to convert AC line voltage to some lower level, rectify the AC voltage and finally provide filtering to remove residual AC ripple from the DC output voltage. Very few electronic systems actually depend on AC voltage at the circuit level and it is the function of the system power supply which makes the conversion from line voltage to the working voltage(s) of the system.

Characteristic	Linear	Switching
Size	$0.5W/in^3$	$2W/in^3$
Weight	$10W/lb$	$50W/lb$
Efficiency	30%	80%
Output Ripple		
Peak-to-peak	1.0 mV	50 mV
Rms	-	10 mV
Transient Time		
Constant	25 μs	500μs
Line Carryover	2 ms	20 ms
Line Tolerance	± 10%	± 20%
Regulation	0.1%	0.1%

Table 12. Comparison of specifications for linear and switching power supplies [76].

Linear Power Supplies

The linear power supply has been the most common type of power supply found in electronics, although it is steadily losing ground to the newer switching supplies found in computers and other electronic devices. In its simplest form, a linear power supply consists of a step-down transformer, a series or shunt transistor regulator, rectification components and filtering to remove the ripple from the DC output. Linear supplies provide good voltage regulation, but they are large, bulky, and are characterized by a typical efficiency of approximately 40%.

Because of the relative inefficiency of linear power supplies, they normally require extensive cooling, especially for the voltage regulating pass transistor which requires a large heat sink. Another large component is the 60 Hz transformer which provides the interface between the AC line input and the rectifier section. The net result is that besides being relatively inefficient, linear power supplies tend to be large and bulky, a problem which has been significantly reduced in switching power supplies.

Linear supplies are relatively easy to design and manufacture and they represent a technology which has been around for many years. It is a mature power supply design technique and many linear regulator circuits are available.

Switching Power Supplies

Switching power supplies are the fastest growing segment in the power supply industry, directly addressing the problems of cost, size, weight, efficiency and regulation. They provide a significantly greater power density than do linear supplies and are used almost exclusively in the microcomputer industry.

The technology used to achieve the improvements over linear power supplies is relatively complex and the early switching supplies were only competitive in the high wattage applications. However, as the popularity of switching power supplies increased, transistor manufacturers started to design devices specifically for switcher applications. Like a linear power supply, switching supplies transform line voltage, usually 60 Hz, to a regulated dc voltage.

In a switching power supply, rectification is done on the primary side of the power transformer and the resulting DC voltage is switched at a frequency above 20 kHz for input to the transformer. Voltage regulation is accomplished by monitoring the supply output voltage and varying the on-time to off-time (pulse-width-modulation) of the switched waveform.

By operating above 20 kHz, switching power supplies can generate a significant amount of electromagnetic interference (EMI) and extensive filtering is required to meet FCC regulations. The *LC* filtering circuits in the power supply store enough energy to provide from 15 to 35 ms of ridethrough. Some power supplies have been known to provide as little as 8 ms and as much as 50 ms [40]. They also serve to prevent external noise signals from penetrating into the logic circuits of the machine and, despite the warnings given by the manufacturers of noise filtering devices, power line noise does not appear to be a major problem for small computer installations.

PC Tolerance of Powerline Disturbances

During this study an IBM PC XT was subjected to low constant rms line voltages to ascertain the operating characteristics of the computer at low voltage levels. The power supply used in the PC was a contemporary switching power supply commonly used in both the IBM machines and compatibles. A single-phase variable

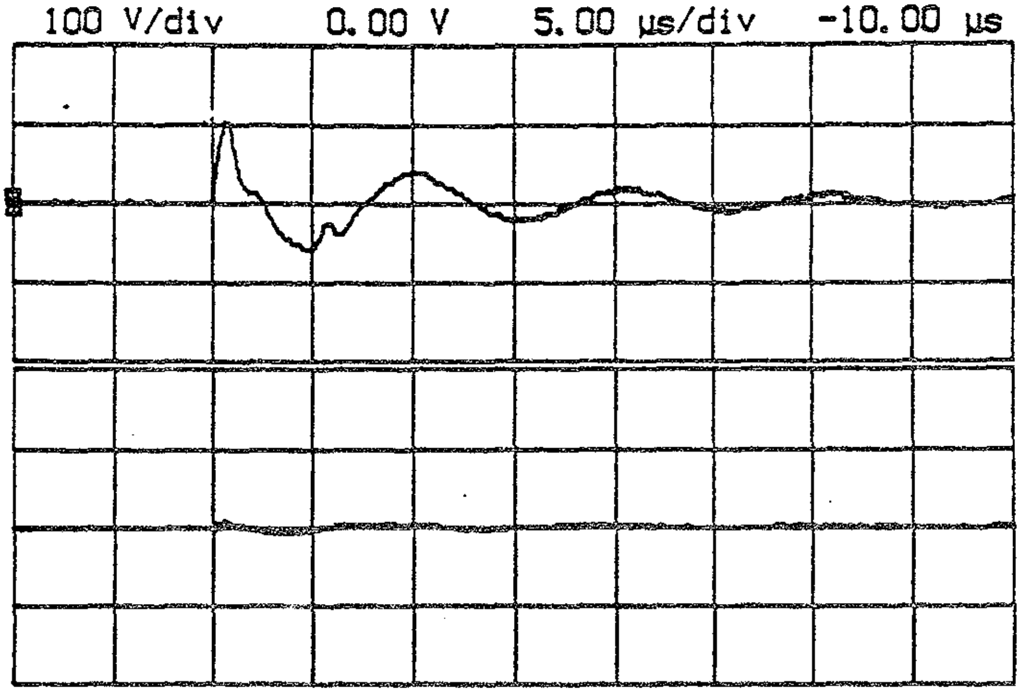


Figure 26. IBM PC XT response to a 400 V ringwave superimposed on the input voltage peak. Top: 400 V normal mode ringing impulse. Bottom: 5 V_{dc} power supply voltage rises to 5.77 V.

transformer was used to supply power to the computer. The supply voltage was gradually reduced from 120 V_{rms} and observations of both the monitor display and the computer operation, as determined by machine response to DOS commands, were recorded as the supply voltage was lowered.

At 100 V_{rms} the computer was still responding to DOS commands. However, the monitor display began to become unsteady and wobbled noticeable at 100 V. Below 100 V the display began to gradually shrink in the vertical axis as the voltage was lowered but the computer responded correctly to DOS instructions. Further reductions in powerline voltage aggravated the monitor display in proportion to the voltage level. At 70 V_{rms} the display was barely legible but it could still be verified

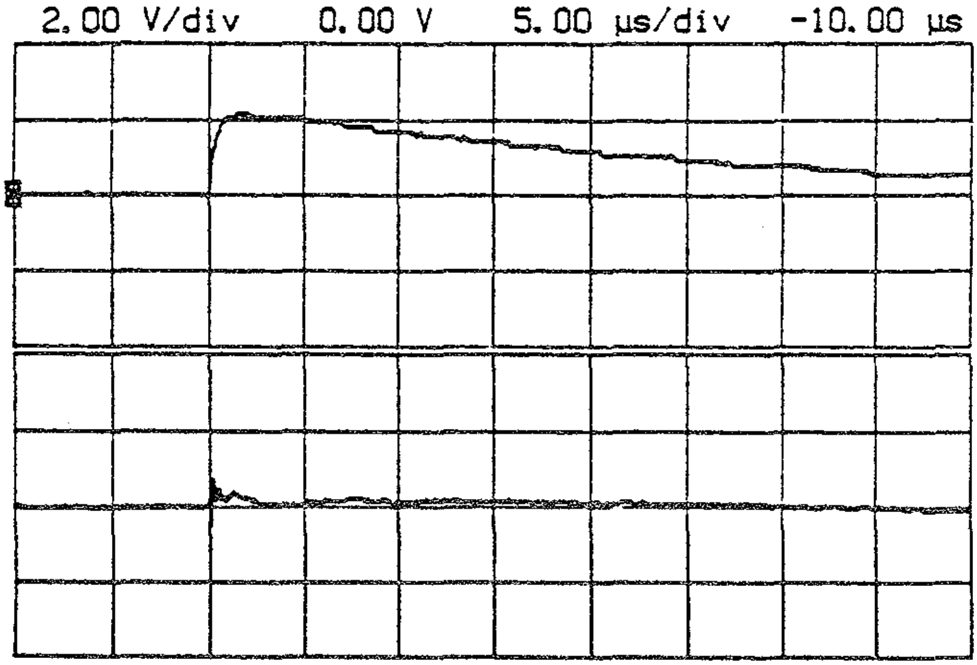


Figure 27. IBM PC XT response to a 400 V unipolar impulse (1.2 x 50μs). Top: 400 V normal mode incident impulse. Bottom: IBM power supply voltage rises to 7.8 volts for less than 1 μs.

that the computer was responding to DOS commands. At 64 V_{rms} the computer power supply shut down.

Nominal 120 V_{rms} AC voltage was then restored to the system and the computer booted normally. The input voltage was again reduced with the same result; the display shrinking in proportion to voltage and the computer logic showing no signs of malfunction down to 64 V_{rms} at which time the power supply shut down. The procedure was repeated six times with the same result.

An identical IBM machine was subjected to impulse voltages of the waveform specified in IEEE C62.45-1987, Category A, at magnitudes between 100 V and 6.0 kV. Impulses of positive polarity were applied to the power cord of the computer and inserted on the peak of the positive half-cycle of the supply voltage using the KeyTek 587 surge generator. The impulse were applied in the normal mode, between line and

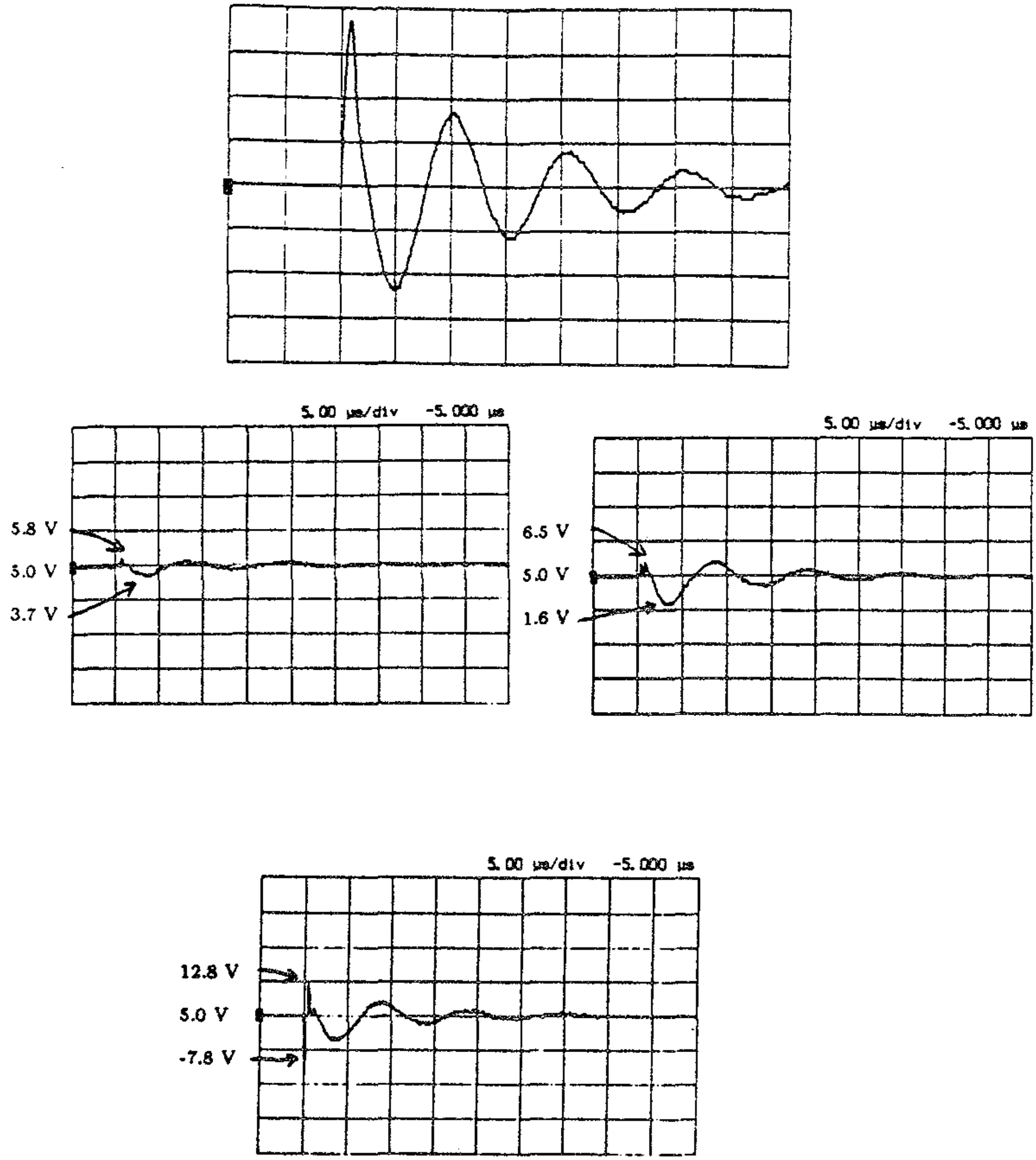


Figure 28. IBM PC XT response to high magnitude normal mode ringwaves. Top: IEEE Category A ringwave at 6.0 kV. Middle left: 5 V IBM power supply response to a 1.0 kV ringwave applied in the normal mode. Middle Right: IBM power supply response to a 3.0 kV ringwave. Bottom: IBM power supply responds to the 6.0 kV, IEEE Category A surge.

neutral. Monitoring of the computer during the impulse tests was done at the 5 V_{dc} (logic power) output of the computer power supply. During the tests the computer was running a series of simple arithmetic calculations in BASIC. It was assumed that likely failure modes resulting from the tests would either be catastrophic damage to the computer, halted execution of the program, or the introduction of mathematical errors which would appear on the monitor. The monitor itself was isolated from the impulses.

Figures 26, 27 and 28 show the transient response of the 5 V_{dc} bus of the computer power supply at the various impulse magnitudes. The computer functioned normally during all tests, including the full 6.0 kV, IEEE C62.45 Category A impulse. The ability of the PC to withstand fast-rising impulses of this magnitude was suggested by the results previous high-voltage impulse testing of IBM compatibles [55], the results of which were consistent with the tests under the Rural Alaska Power Quality study [3].

CHAPTER 7

COMPARING DEVICE EFFECTIVENESS FOR RURAL DISTURBANCES

Voltage Regulation

Most commercial voltage regulators and power conditioners operate either by electronic tap-changing or by ferroresonance. Both types exhibit similar regulation characteristics under full load conditions (Figures 8, 33, & 34). The regulating characteristics of the ferroresonant devices, however, improve over tap-changing regulators if operated at less than rated load. The tap-changing regulators do not exhibit the smoothness in regulation of the ferroresonant types due to the incremental nature of voltage changes as taps are being switched but this should be inconsequential from the load perspective as long as the regulator output remains within the accepted voltage operating envelope of electrically sensitive loads. Single tap changes are made in 1/2 cycle. If more than one switching operating is required to compensate for large voltage swings the sequence is normally completed within a few cycles, depending on the rate of collapse ($\frac{dv}{dt}$) of the supply voltage.

Ferroresonant transformers have one outstanding quality for use in Alaska. With no semiconductor components or moving parts they should have essentially the same lifetime expectancy as other power transformers. Tap-changing regulators have complex circuitry and undoubtedly higher failure rates. This difference can have significant consequences in remote areas where equipment downtime during servicing is often long and usually expensive. In the villages, a device in need of simple repairs is often discarded because the owner is unfamiliar with the equipment and may not know the extent of damage. Therefore, equipment which can provide many years of maintenance-free service should receive serious consideration for arctic use.

The major disadvantage of ferroresonant transformers is low efficiency which can be a significant factor to those who directly incur the monetary cost of electric power in rural areas. Ferroresonant transformers typically dissipate 15-20% of their wattage rating under no load conditions. A 500 VA ferroresonant transformer, the

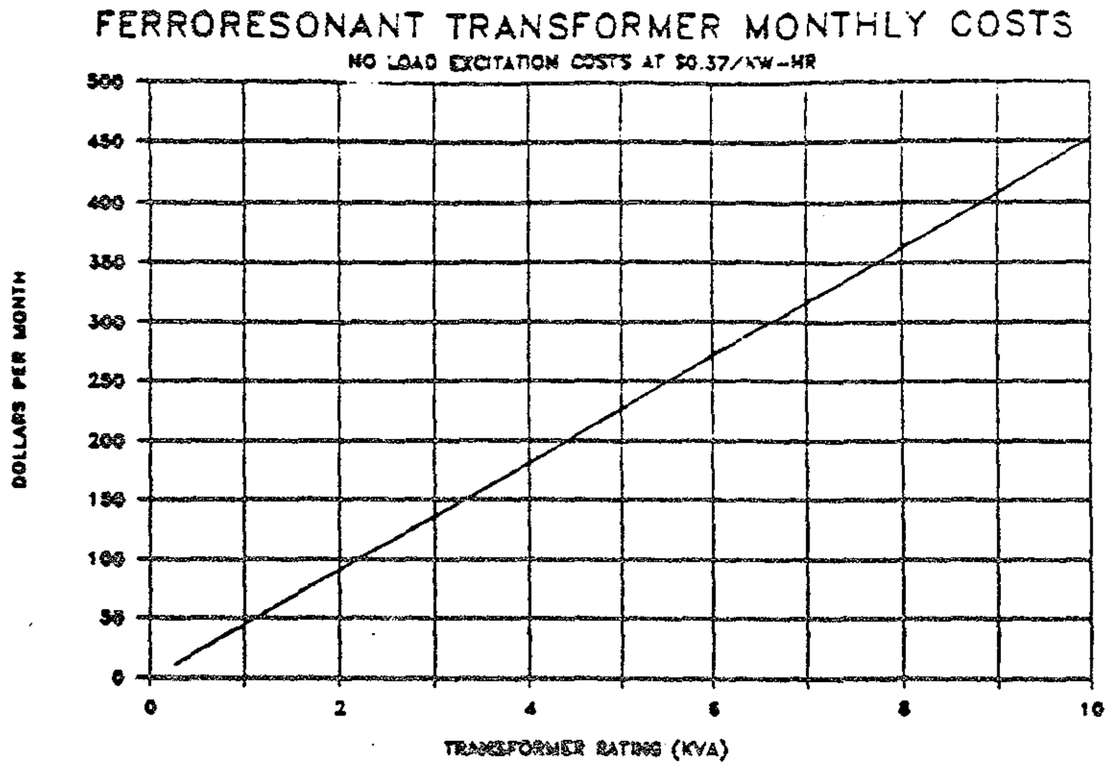


Figure 29. Typical no-load excitation costs of ferroresonant transformers at 37¢ per kilowatt-hour.

approximate size required to power two microcomputers, will require about 80 watts continuously while the transformer is energized, even when the device is unloaded. At typical village power rates this can add up to $20 to $30 in additional monthly power costs if the transformer is continuously excited throughout the month. Figure 29 plots the approximate no load operating costs of ferroresonant transformers of varying size based on a village power rate of 37¢ per kilowatt-hour. From this information it can be seen that large ferroresonant transformers can be expensive to operate if they are located on the load side of a utility kilowatt-hour meter.

Ferroresonant transformers should be sized carefully if motor loads are present due their high impedance and inability to deliver high inrush currents. Light overloads merely degrade regulation. As the overload increases, a point is reached where

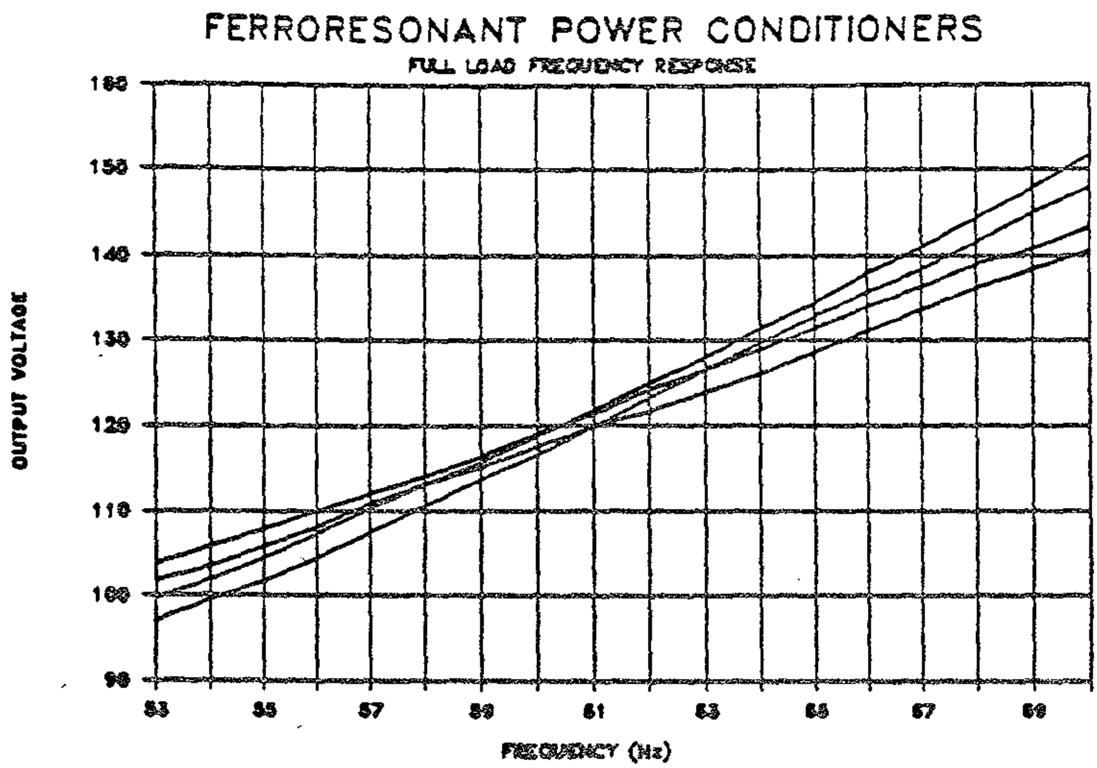


Figure 30. Output voltage vs. frequency for four ferroresonant transformers under full load. Output voltage changes approximately 1.5 percent for a 1 percent change in input frequency. Input voltage was held at 120 V_{rms}.

the output voltage collapses and, at short circuit conditions, the load current is limited to approximately 200%. The maximum starting current to motors should therefore be determined and the ferroresonant transformer capacity selected accordingly. A single ferroresonant transformer should not be expected to deliver greater that 140% of its full load current rating without the possibility of rapid output voltage collapse. Single-phase units of the same size can be paralleled to provide greater load capacity.

Ferroresonant transformers typically add 3 to 5 percent harmonics to the AC sinewave which will cause motors to operate slightly hotter but should have little effect on other equipment. Tap-changing regulators do not alter the input waveshape.

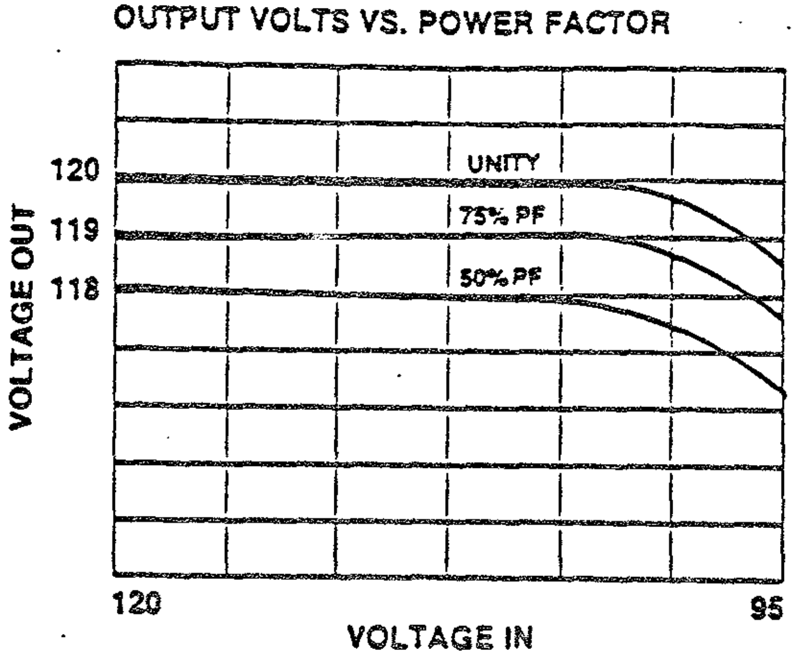


Figure 31. Output voltage vs. load power factor for Rapid 500 VA ferroresonant transformer.

Tap-changing regulators attenuate common mode transients well if isolated windings are used but require varistors or other design modifications if normal mode transient attenuation is to be offered. Even so, tap-changing regulators tested for this project rivaled many computer surge suppressors in normal mode impulse attenuation. Ferroresonant devices provide good transient attenuation in both normal and common modes eliminating the need for additional surge suppression circuitry within the unit.

Tap-changing regulators have a higher efficiency which may be the decisive factor if 24 hour continuous duty is required and the equipment owner is paying for transformer losses at typically high village electric power rates. They have a lower impedance than ferroresonant transformers and can deliver greater starting currents to loads, although individual models differ and sizing considerations should be made where motor loads exist.

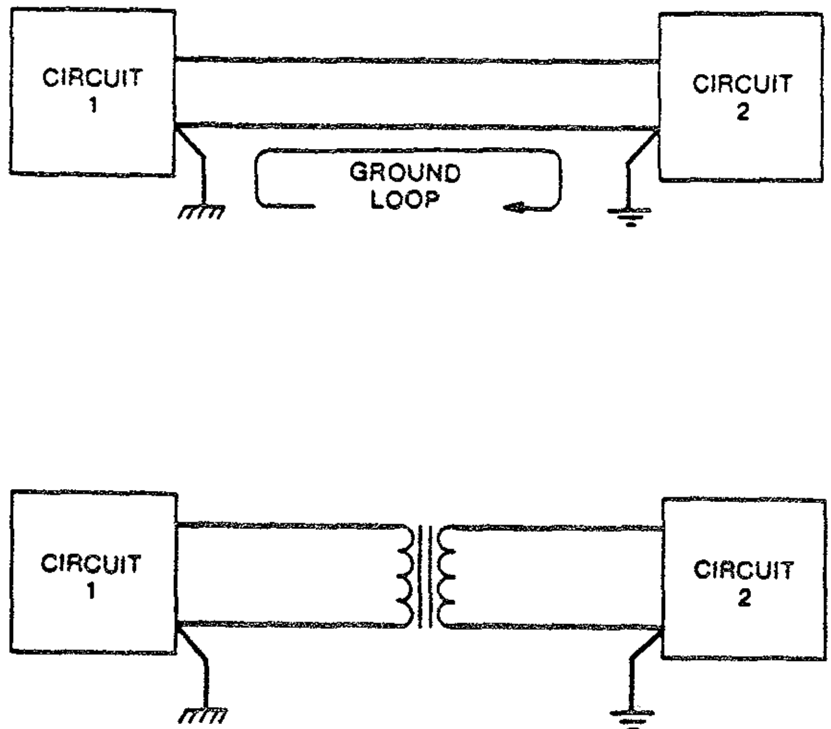


Figure 32. An isolation transformer configured to break a ground loop between two circuits.

Isolation

Isolation transformers are often misrepresented as being the cure-all for power-line problems. Isolation implies immunity from common mode voltages. Common mode voltages occur when electric currents circulate in inadvertent, sometimes unavoidable ground loops in circuits (Figure 32). Computer networks can experience errors where many devices are interconnected and sharing common shielding paths.

The function of isolation transformers is to suppress common mode noise and to break ground loops, but they are less effective in attenuating surges that occur line-to-line (normal mode). Many normal mode signals, which comprise the vast majority of serious transients voltages, pass through an isolation transformer and claims other than common mode noise rejection should be viewed cautiously. Figure 35 illustrates the inability of an isolation transformer (in this case in the form of a tap-changing power conditioner) to adequately suppress low voltage noise appearing in the normal mode. The performance of a straight high-isolation transformer should not be expected to differ significantly.

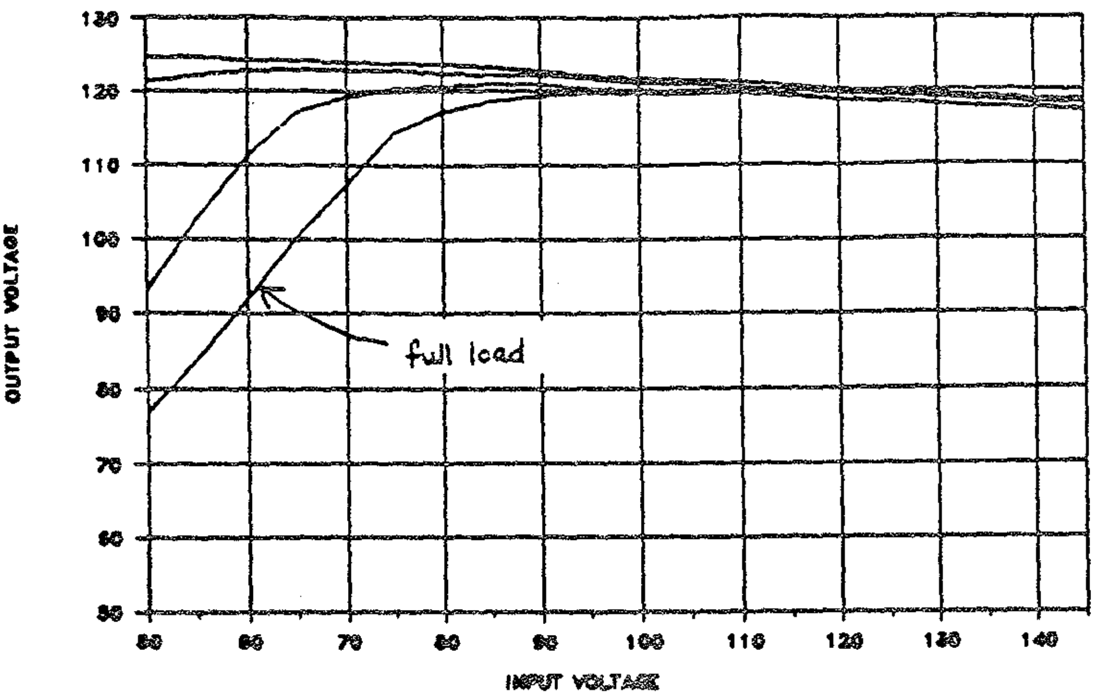
Although both power conditioners represented in Figure 35 are isolating voltage regulators, the input noise signal appears in the normal mode, where common mode isolation is ineffective. There is no need for voltage regulation because the rms line voltage has not been measurably altered by the noise . The relative success of the ferroresonant conditioner is due to clipping of the normal mode signal in the saturated ferroresonant secondary.

Even where common mode signals are known to be a problem, many ferroresonant or tap-changing power conditioners provide excellent common mode rejection, typically 120 dB, and also provide voltage regulation. An isolation transformer cannot regulate voltage or provide backup power in the event of a blackout and should therefore be discounted for rural power conditioning unless ground loops are known to present problems. If grounding loops exist then any two-winding transformer should provide adequate isolation at a lower cost than that of a highly shielded transformer.

Uninterruptible Power Systems

Uninterruptible power systems are the only power conditioning apparatus which will supply power to critical loads through the many power outages experienced in small Alaskan systems. The most appropriate UPS systems for rural areas are assumed to be relatively small in capacity and there are many models available in the 500-5000 VA range.

Off-line UPS systems, which switch on the inverter power supply during a substantial voltage fluctuation, should be preferable over the true UPS based on low inverter efficiencies. Off-line UPS feed utility power directly to loads until voltage ranges beyond unacceptable levels, at which time the inverter is switched on and becomes the power source throughout the duration of the outage or until the inverter battery has become discharged. Because the inverter is only operating occasionally its failure rate can be expected to be lower than comparable true UPS systems, and the user is only paying for inverter inefficiencies while it is on.



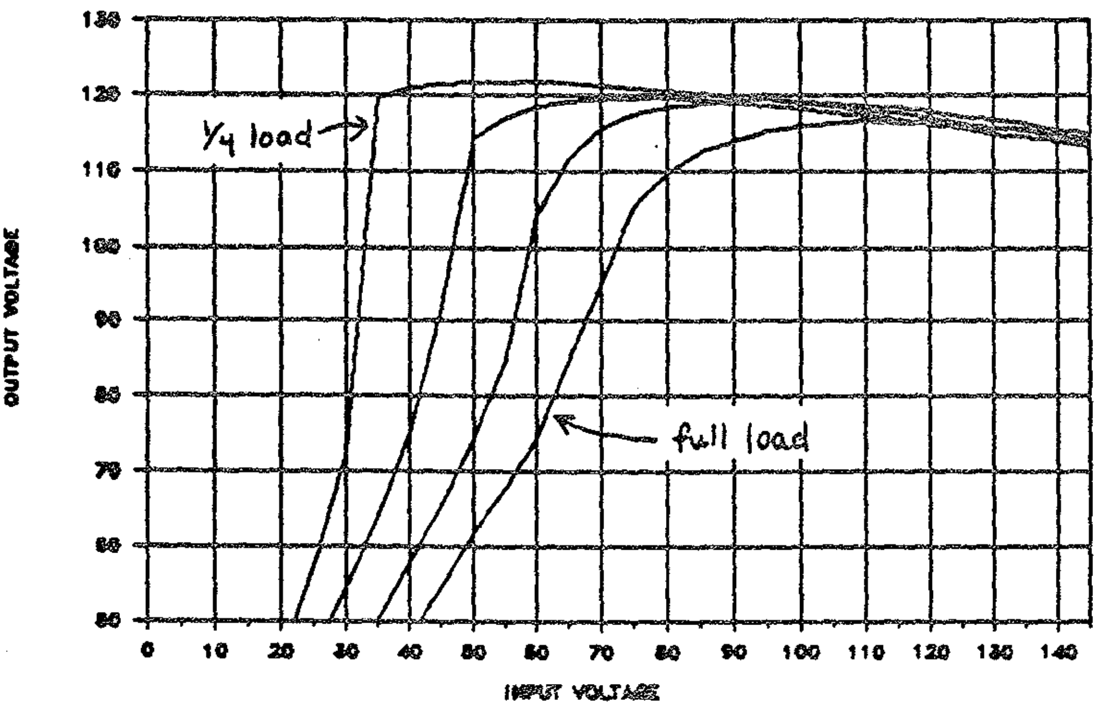
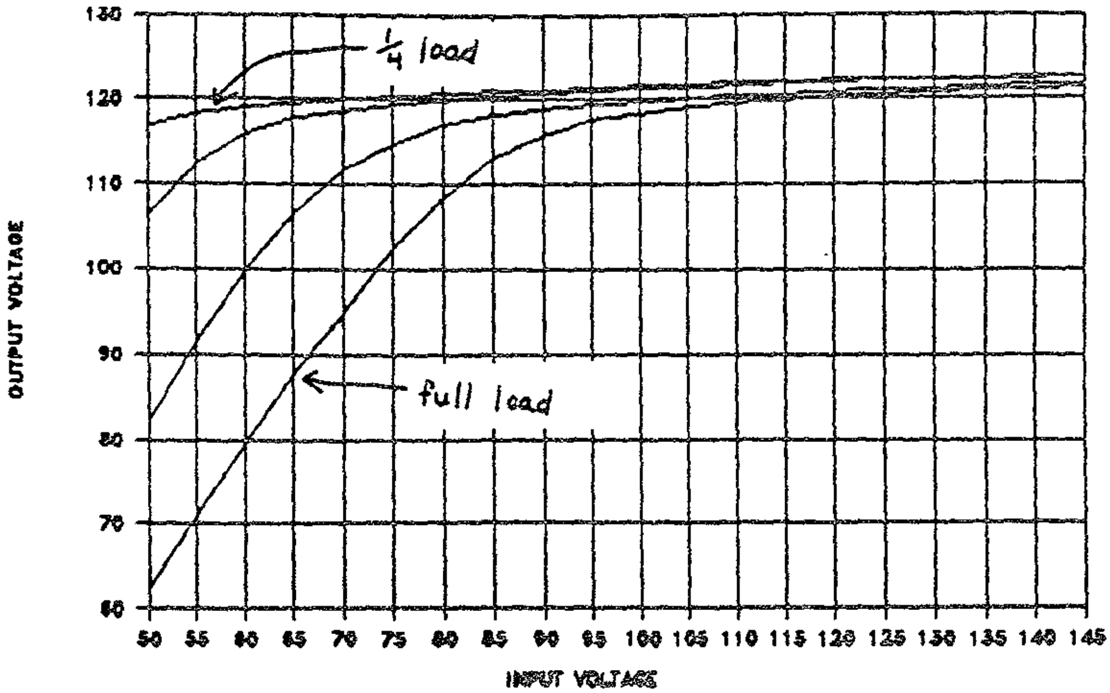


Figure 33. Voltage regulation characteristics for two ferroresonant transformers. Top: Sola 120 VA normal harmonic type Constant Voltage Transformer. bottom: Sola 500 VA sinusoidal output Constant Voltage Transformer.



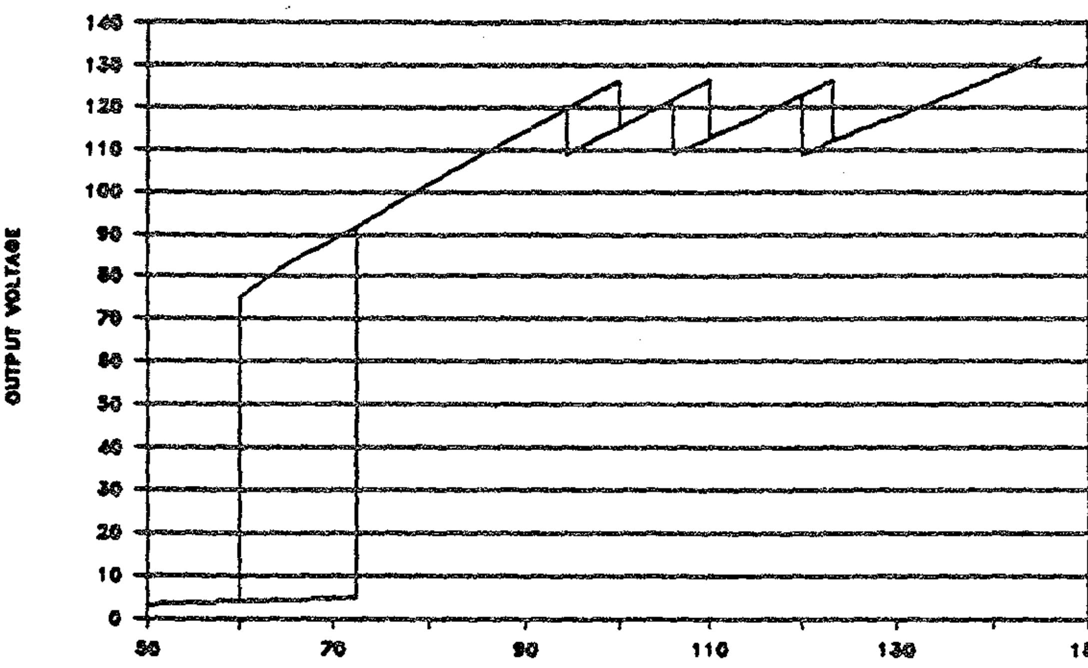


Figure 34. Voltage regulation characteristics for ferroresonant transformer and tap changing power conditioner. Top: 500 VA ferroresonant Rapid Power Technologies FPSAAD50120:A. Bottom: Deltec 500 VA tap changing power conditioner.

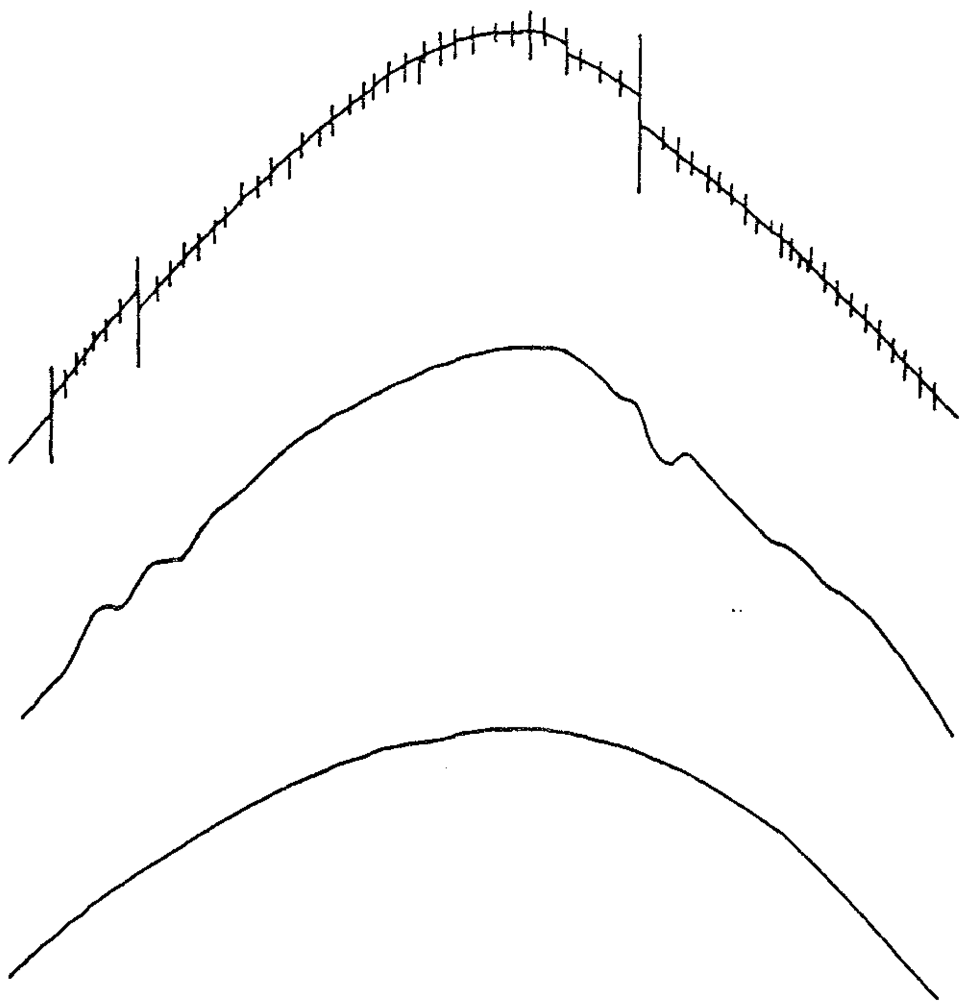


Figure 35. Protection from normal mode line noise created by a 200 hp. solid state variable speed motor drive. Line noise from motor drive (top) represents the input to a tap-changing power conditioner and a ferroresonant transformer. The tap-changing conditioner output (middle) shows distorted output. The ferroresonant output (bottom) reconstructs the noisy voltage wave.

All off-line UPS specify a low voltage inverter cut in point. Some also specify a high voltage threshold. Few manufacturers mention a low frequency cut in, although some incorporate this feature into their products and this should be considered advantageous for use in small diesel generating systems.

Computer Surge Suppressors

Although some surge suppressors performed well at low-magnitude impulse levels as measured in Alaska, many of those tested passed transients of less than 200 V through to equipment. While these transients may not cause immediate and catastrophic failure of electronic equipment, they tend to degrade semiconductor components over a period of time.

The suppressors tested in this study were consistent. Identical impulses were repeatedly limited to approximately the same magnitude for each device, although the protection levels varied between devices and with impulse magnitude. These results are in contrast to previous computer surge suppressors tests in [55] where it is stated that "A device may limit one surge and let another identical surge pass through nearly unattenuated."

Rural power quality studies indicate that many low-magnitude/low-energy impulse voltages are present in villages and other small isolated systems. The random selection of a surge suppression device to mitigate this particular type of disturbance, including power line noise, may be an ineffective solution. In a lightning prone region, however, this is not the case as even the cheapest suppressors severely limited the 6 kV impulse, an unlikely event in rural Alaska. Low level transients can be better dealt with by employing a commercial power line filter.

Summary

The most effective and practical power conditioning design for critical electrical loads in rural Alaska is an off-line uninterruptible power system with the following attributes.

1. Provisions for connecting external batteries to increase the backup time of the unit. The UPS user should consult manufacturers concerning the ability of UPS battery charging circuitry to adequately recharge additional batteries.

2. The UPS should respond to both low voltage and low frequency conditions. It should not be assumed that voltage will drop proportionately with frequency. It is therefore essential that the unit not only initiate inverter operation at low frequency ($\simeq$ 56 Hz), but that UPS circuits can themselves withstand severe low frequency input voltages without damage.

3. The use of MOVs uptream from the UPS to protect UPS circuity and critical loads in the event of a high voltage transient. Most UPS systems include MOVs as surge suppression components but this should be confirmed prior to purchase.

The most attractive method of protecting essential loads from electrical transients is to use a ferroresonant transformer with the off-line UPS. Again, the high operating costs of the ferroresonant conditioners should be considered prior to implementing this strategy. The conditioner should be placed uptream from the UPS to regulate the UPS input voltage. This will prevent the UPS inverter from operating during steady-state low voltage conditions which inevitably occur in small power systems. The ferroresonant conditioner will also suppress impulse transients in both normal and common modes.

Further studies may need to be conducted to characterize the relationship between sagging voltage and frequency in small systems and their effect on motor loads. A UPS sized to operate a particular motor will provide the best protection as long as the UPS responds to both disturbances. But for nonessential motor loads, where protection is required only to prevent motor damage, a regulator may prove to be the most economical power conditioner if it can be shown that the regulator output provides volts per hertz stability to a load which may be damaged by disproportionately sagging voltage and frequency. A viable alternative would be shedding motor loads at the first sign of low frequency and voltage.

Due to the high cost of operating ferroresonant transformers at villages power rates, tap-changing regulators are recommended for consumer applications although the ferroresonant types have the advantage of simplicity and ruggedness.

For environments in which electrical noise is present a commercial power line filter will provide superior protection to that of a surge suppression device. The use of a ferroresonant transformer will, in most cases, eliminate the need for additional noise filtering.

The solutions to power line problems will vary for different load applications and for different rural electrical environments. In economic terms the problem is to assess the costs required

1. to mitigate the electrical disturbnaces from a specific disruptive source (assuming the source has been identified).
2. alternatively, to remove a specific disruptive source.
3. to protect against specific and recurring disruptive conditions of unkown origin.
4. to protect sensitive equipment from the possibility of damage from certain types of electrical disturbances even though such disturbances have not been detected.

Normally, the electrical environment within a facility is not known. Also, the transient stress which equipment can tolerate is not provided by manufacturers, but it can be assumed that equipment which operates properly within a facility is tolerant of it. However, it can not be assumed that the surroundings are electrically harmless to new devices being installed or that new devices may not significantly alter the existing environment.

Appendix A

Voltage Clamping Levels
of Surge Suppressors

SURGE SUPPRESSORS TESTED

1. SL Waber Datagard 315S
2. SL Waber Linegard
3. Waber Datagard DG204
4. Leviton Duplex
5. SL Waber Powermaster
6. Kalglo Electronics Spike Spiker
7. Model PT-L02 (manufacturer unknown)
8. Waber WH7NS
9. Isobar IB-4
10. Microage EFI-453 Turbo-ST
11. Curtis Ruby

Table 13. Commercial surge suppressors tested for protection against impulse voltages measured in rural Alaska.

Normal Mode Ringwave

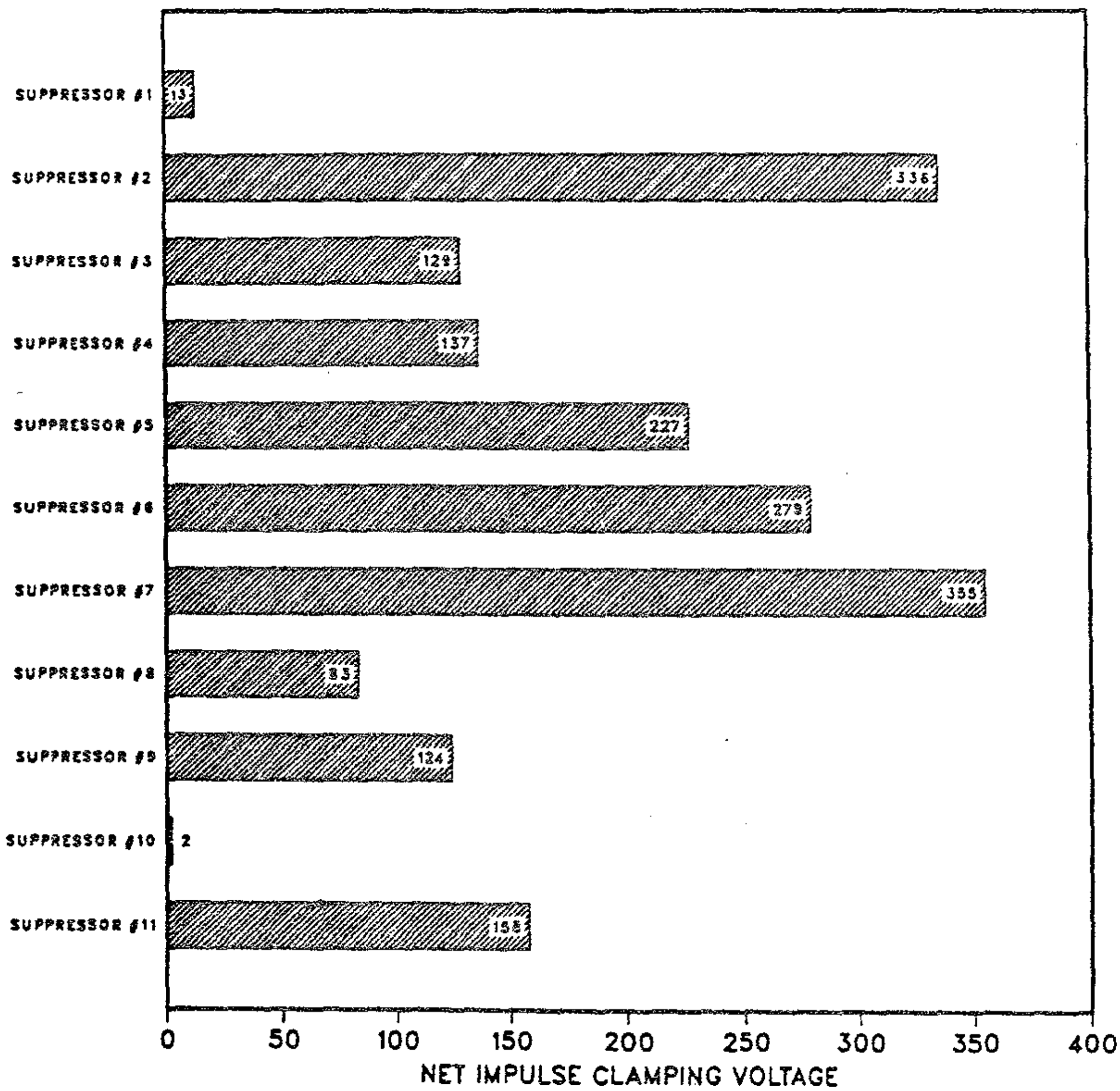


Fig. A-1. Line to neutral voltage clamping levels of surge suppressors to a 400 V normal mode oscillatory impulse.

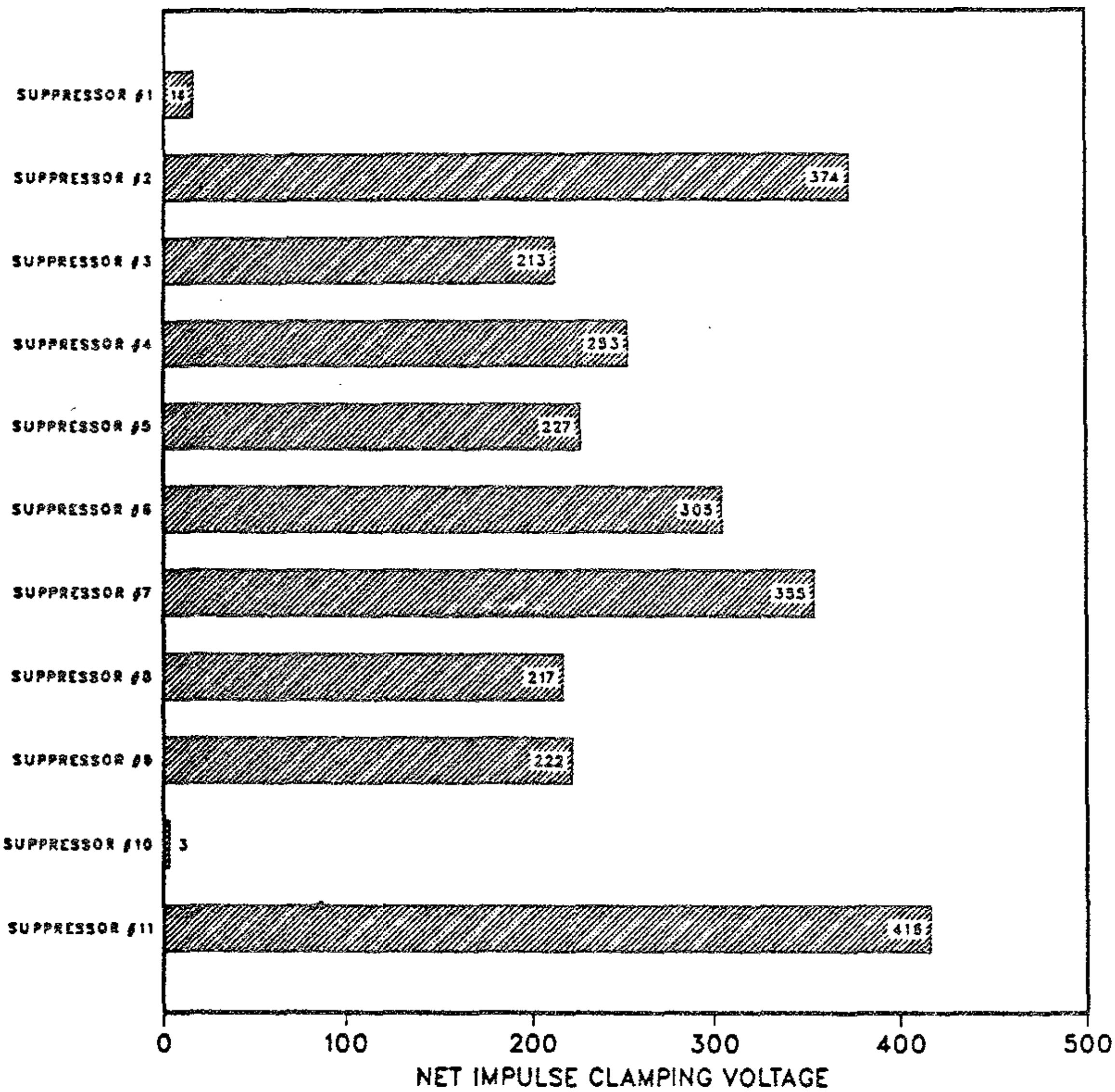


Fig. A-2. Line to neutral voltage clamping levels of surge suppressors to a 1.0 kV normal mode oscillatory impulse.

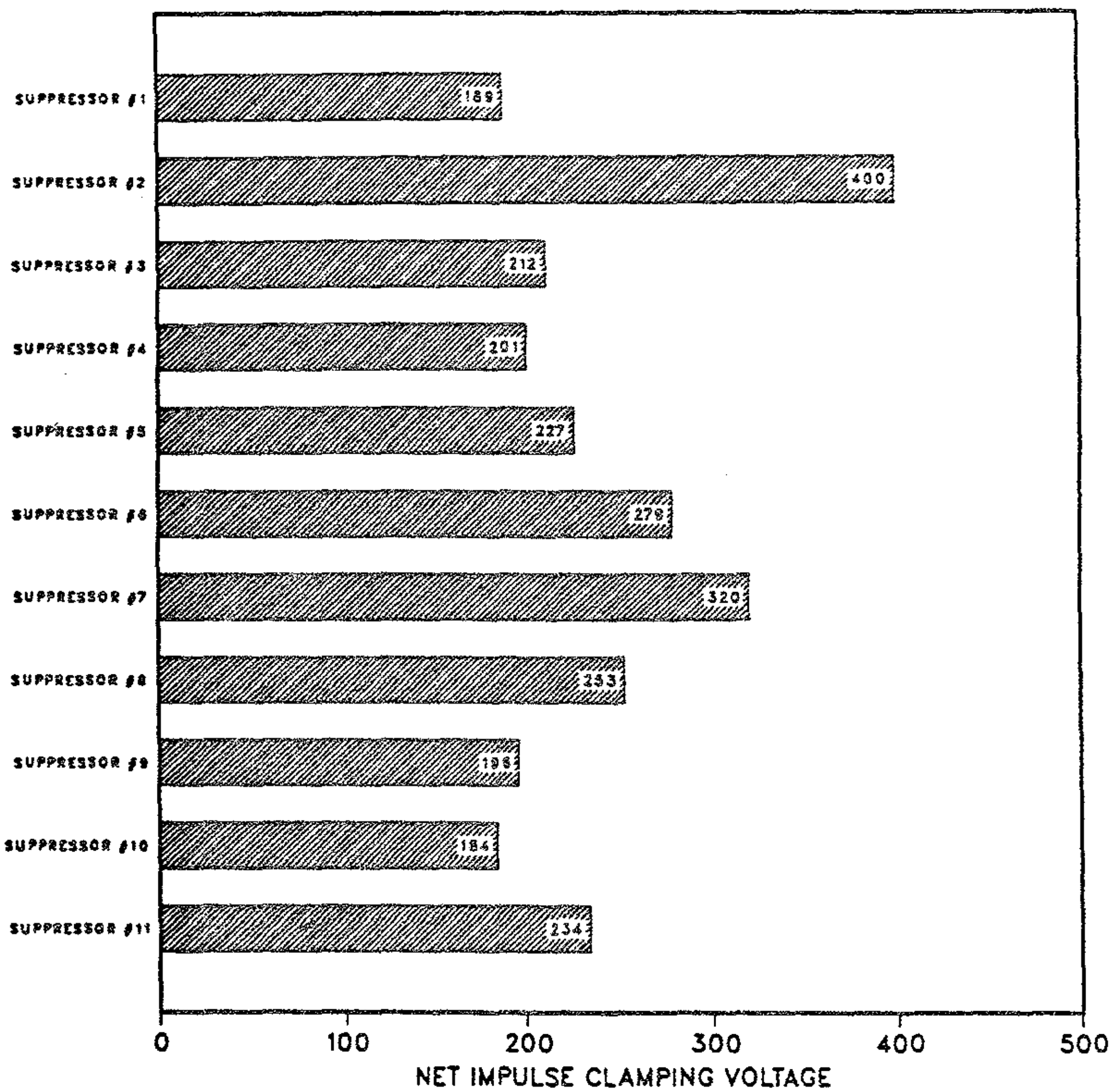


Fig. A-3. Line to ground voltage clamping levels of surge suppressors to a 400 V common mode oscillatory impulse.

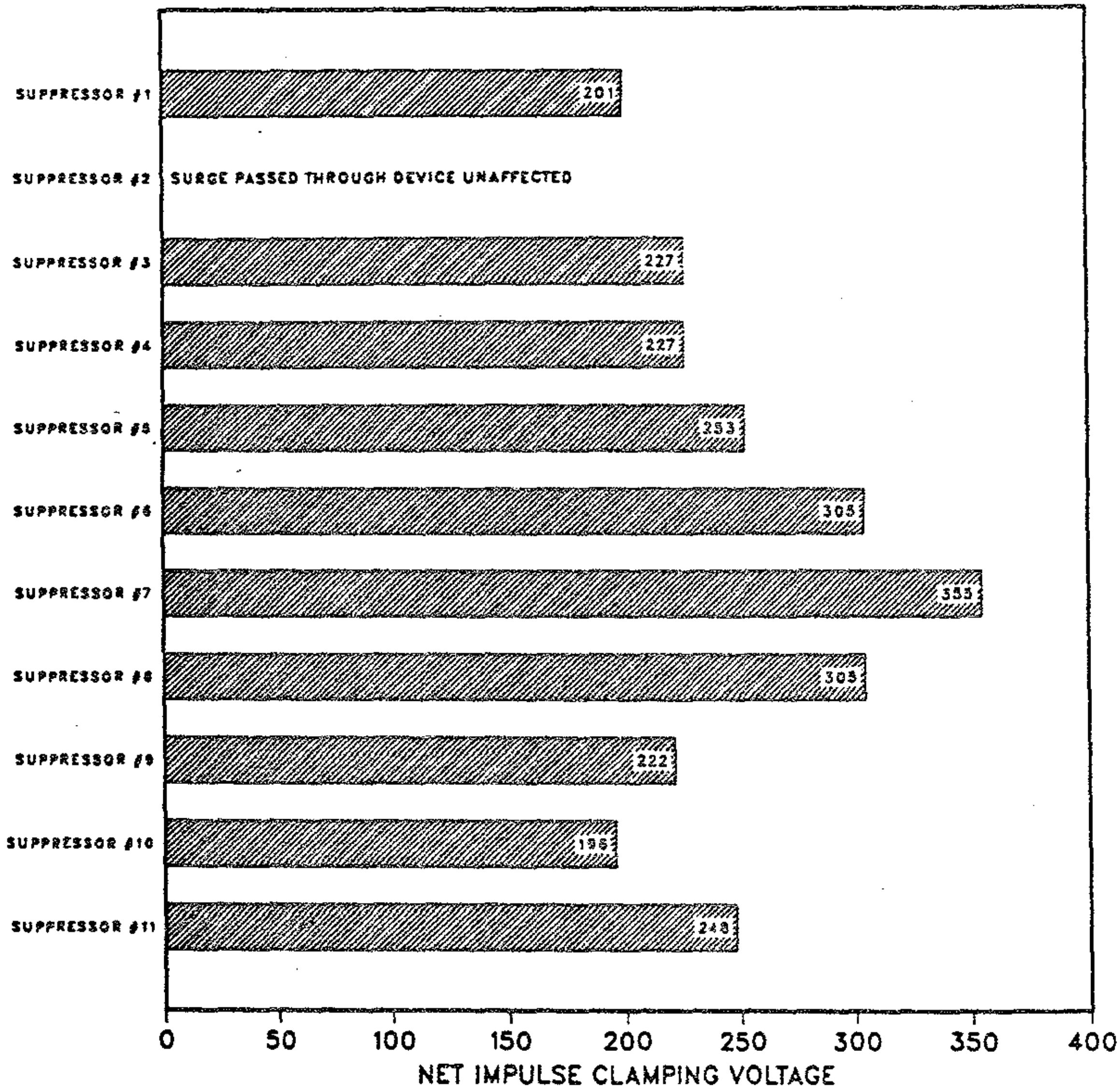


Fig. A-4. Line to ground voltage clamping levels of surge suppressors to a 1.0 kV common mode oscillatory impulse.

Common Mode Ringwave

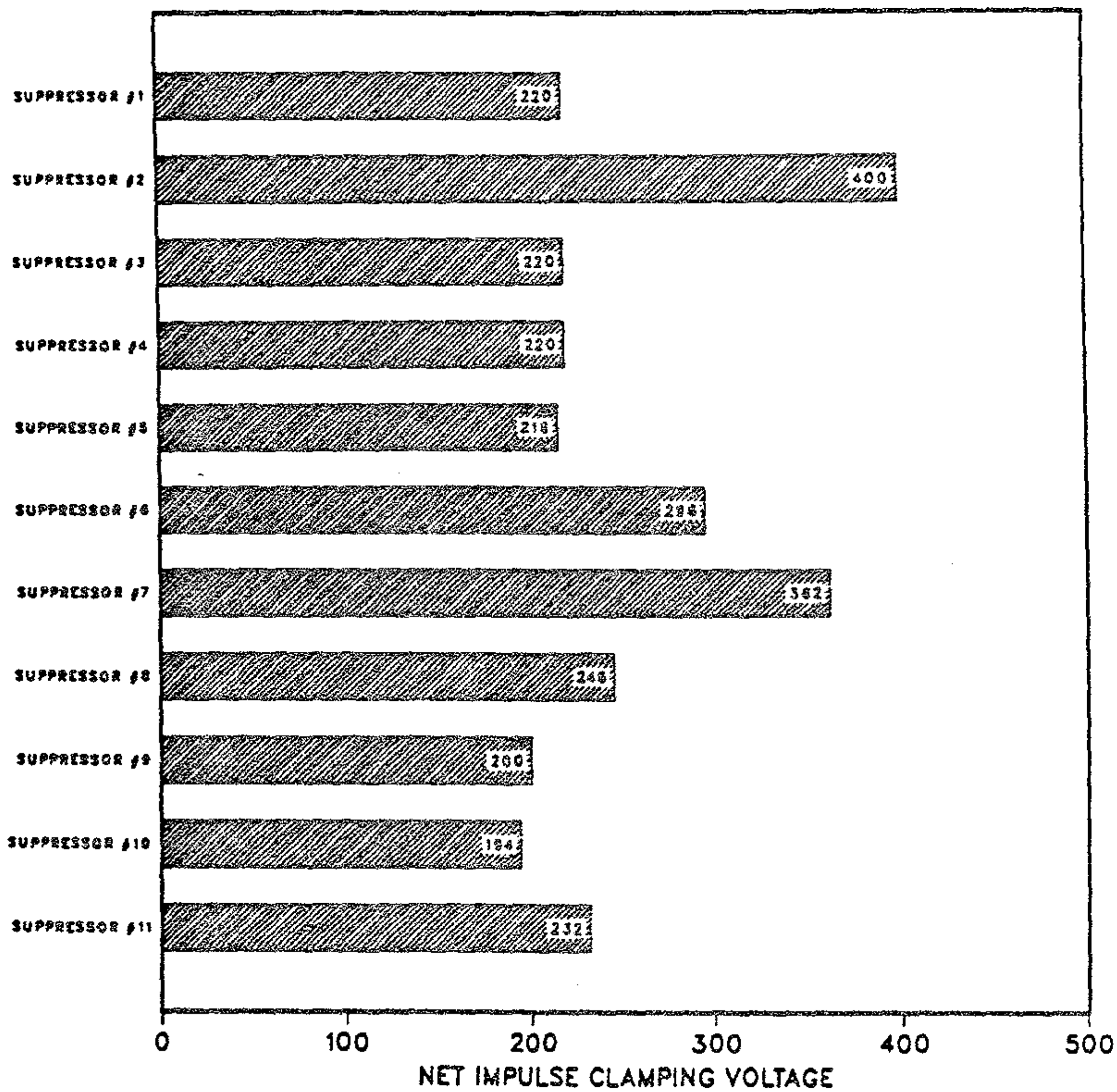


Fig. A-5. Neutral-to-ground voltage clamping levels of surge suppressors to a 400 V common mode oscillatory impulse.

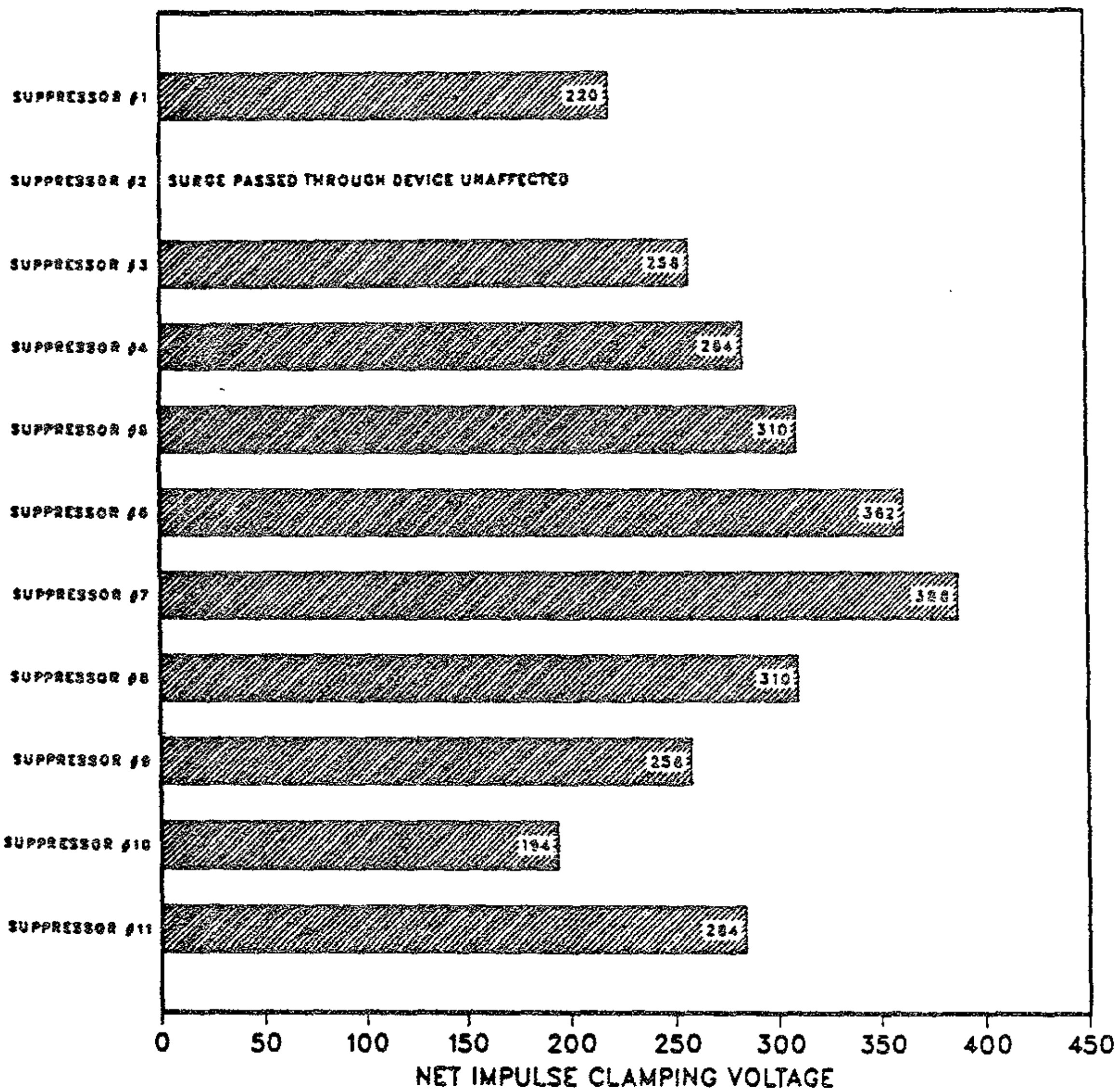


Fig. A-6. Neutral-to-ground voltage clamping levels of surge suppressors to a 1.0 kV common mode oscillatory impulse.

Normal Mode Unipolar Impulse

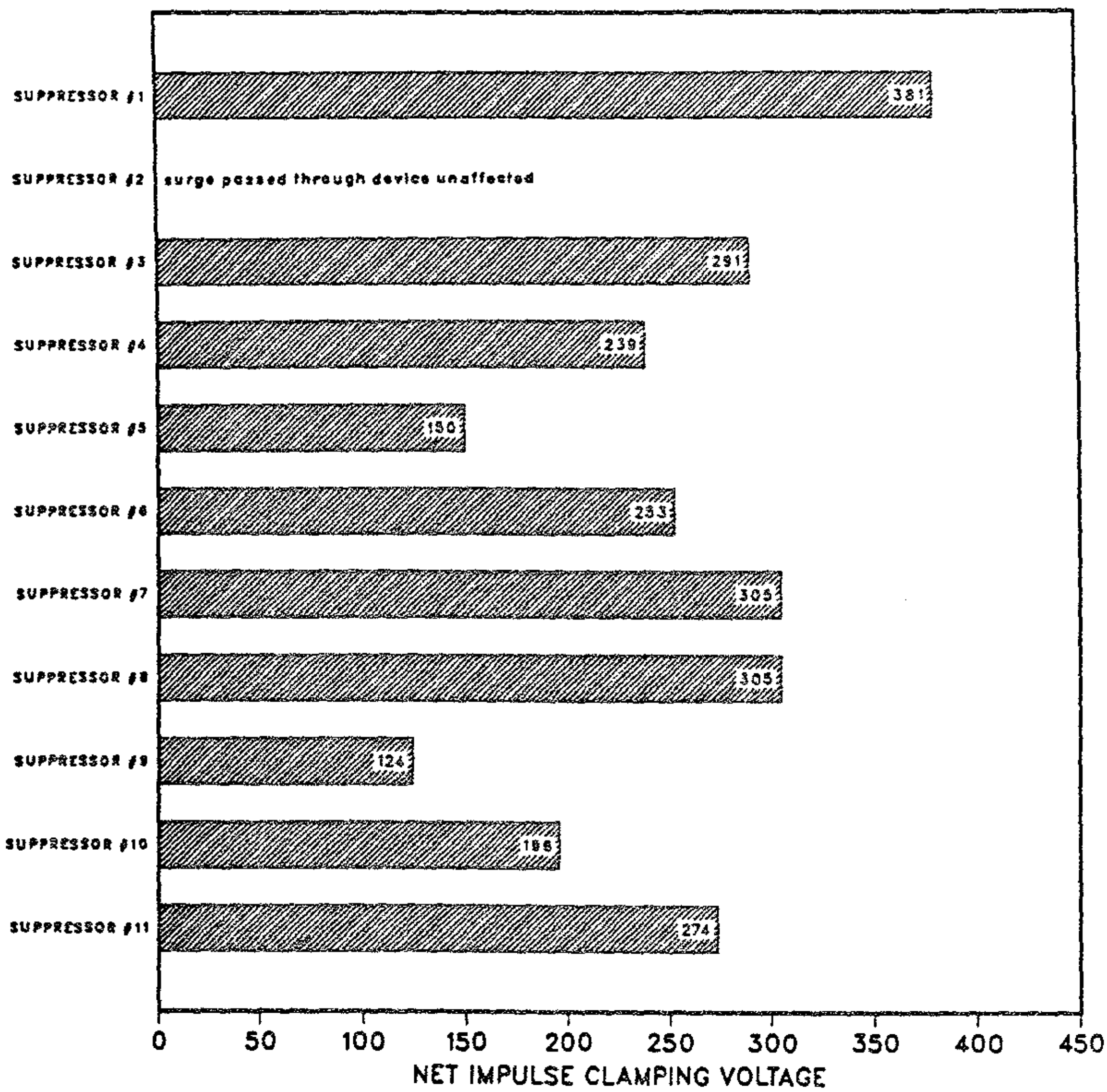


Fig. A-7. Line to neutral voltage clamping levels of surge suppressors to a 400 V normal mode 1.2x50μs impulse.

Normal Mode Unipolar Impulse

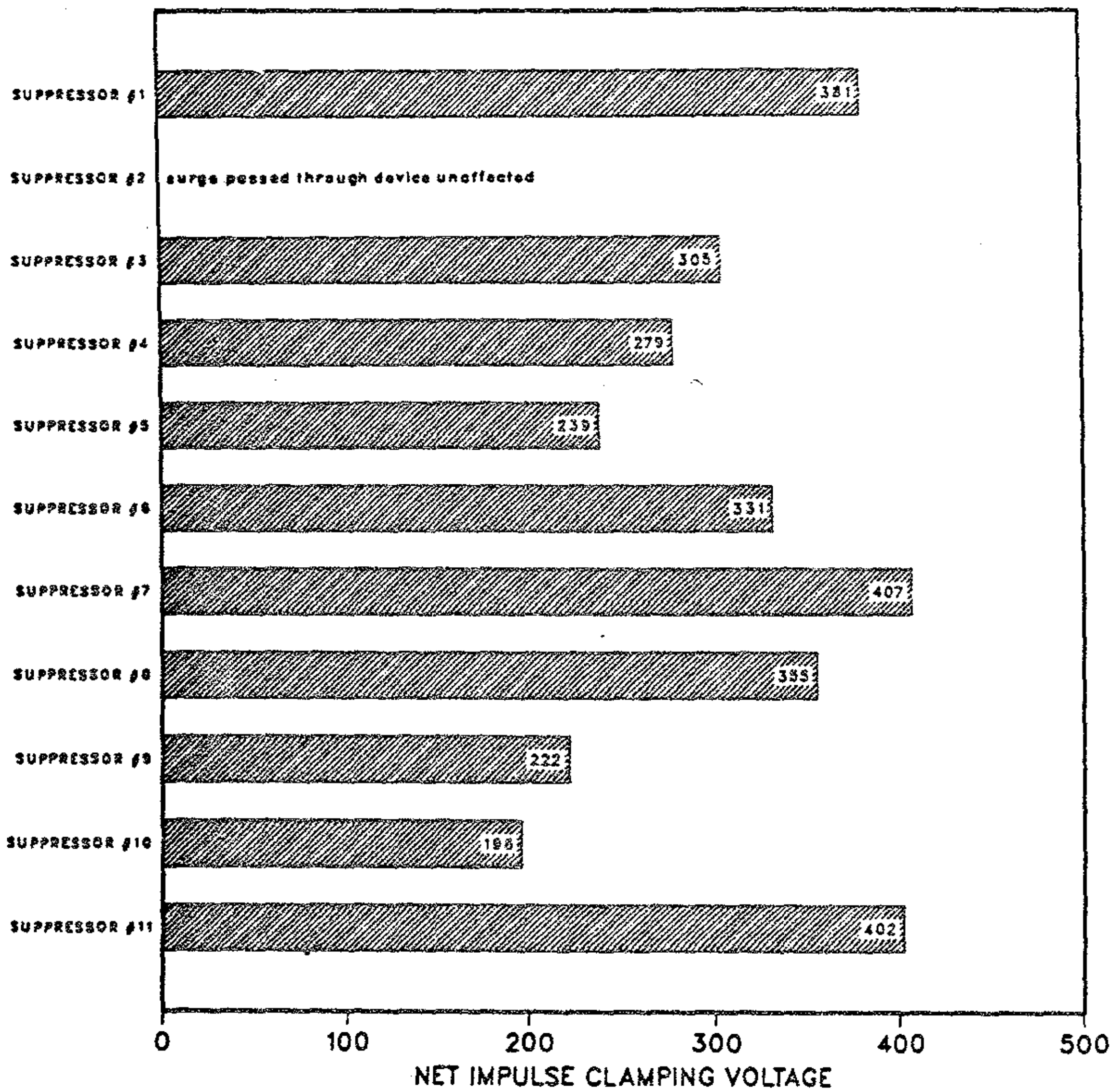


Fig. A-8. Line to neutral voltage clamping levels of surge suppressors to a 1.0 kV normal mode 1.2x50μs impulse.

Common Mode Unipolar Impulse

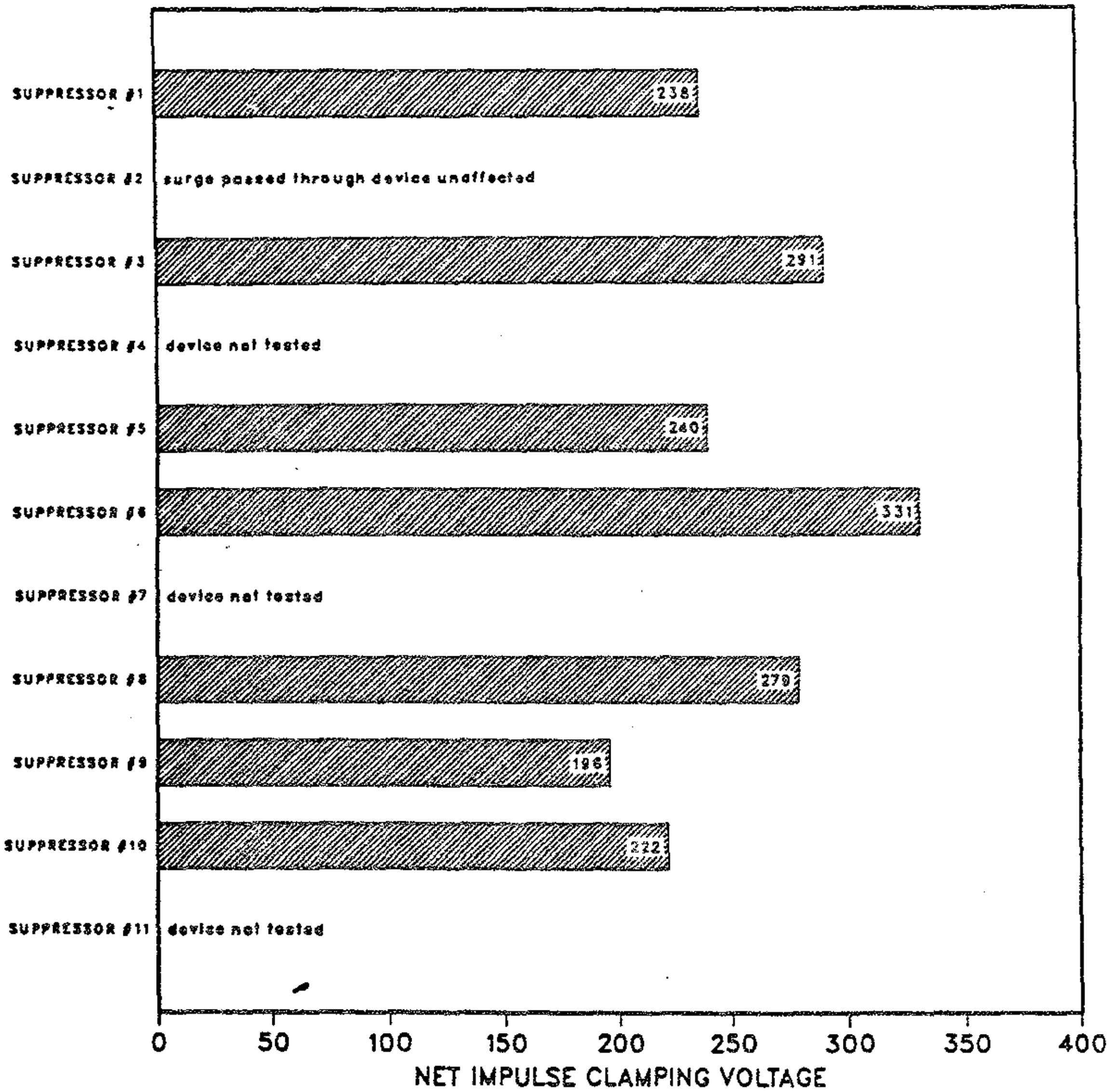


Fig. A-9. Line to ground voltage clamping levels of surge suppressors to a 400 V common mode 1.2x50μs impulse.

Common Mode Unipolar Impulse

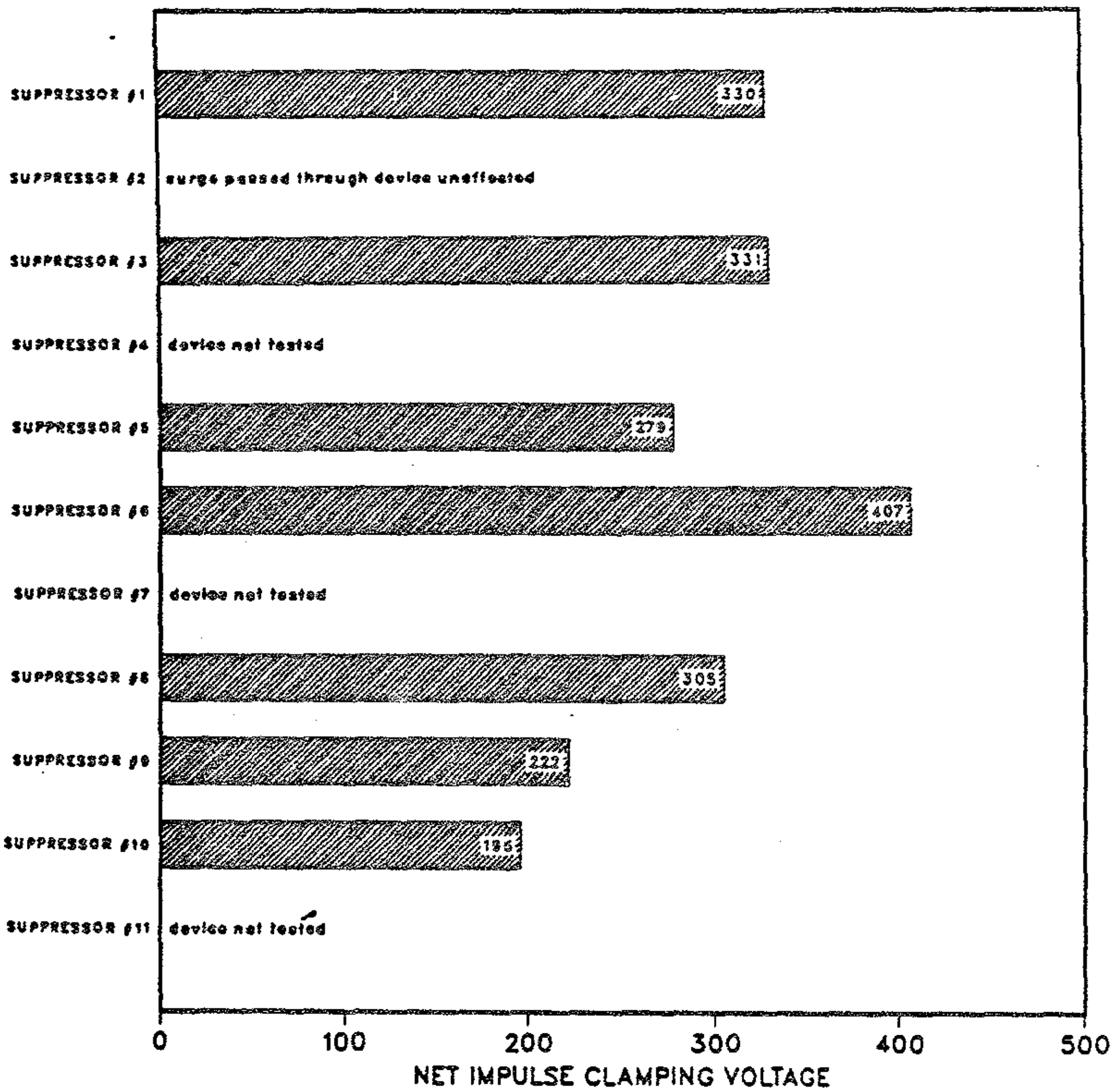


Fig. **A-10.** Line-to-ground voltage clamping levels of surge suppressors to a 1.0 kV common mode 1.2x50μs impulse.

Common Mode Unipolar Impulse

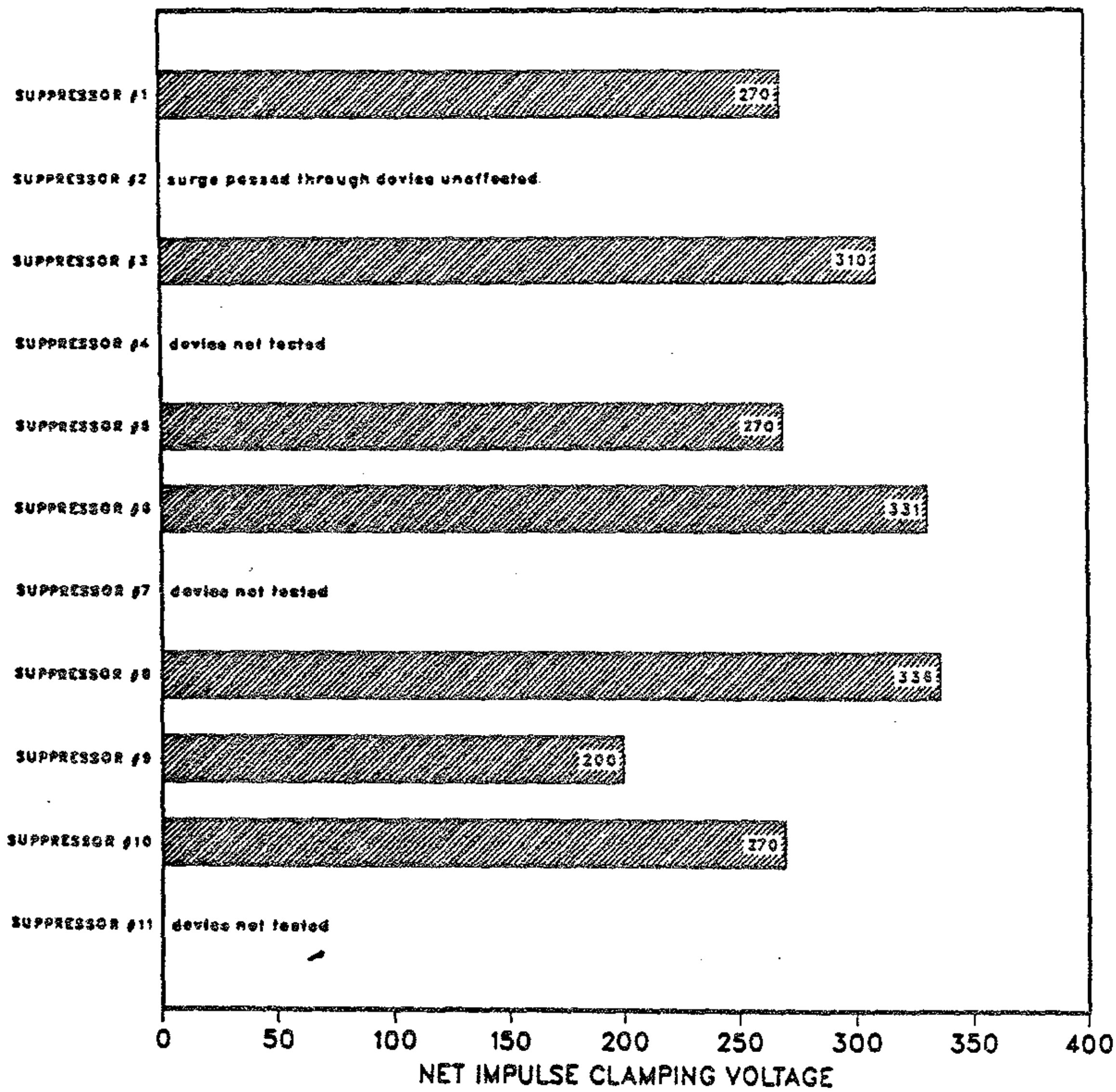


Fig. **A-11.** Neutral-to-ground voltage clamping levels of surge suppressors to a 400 V common mode 1.2x50μs impulse.

Common Mode Unipolar Impulse

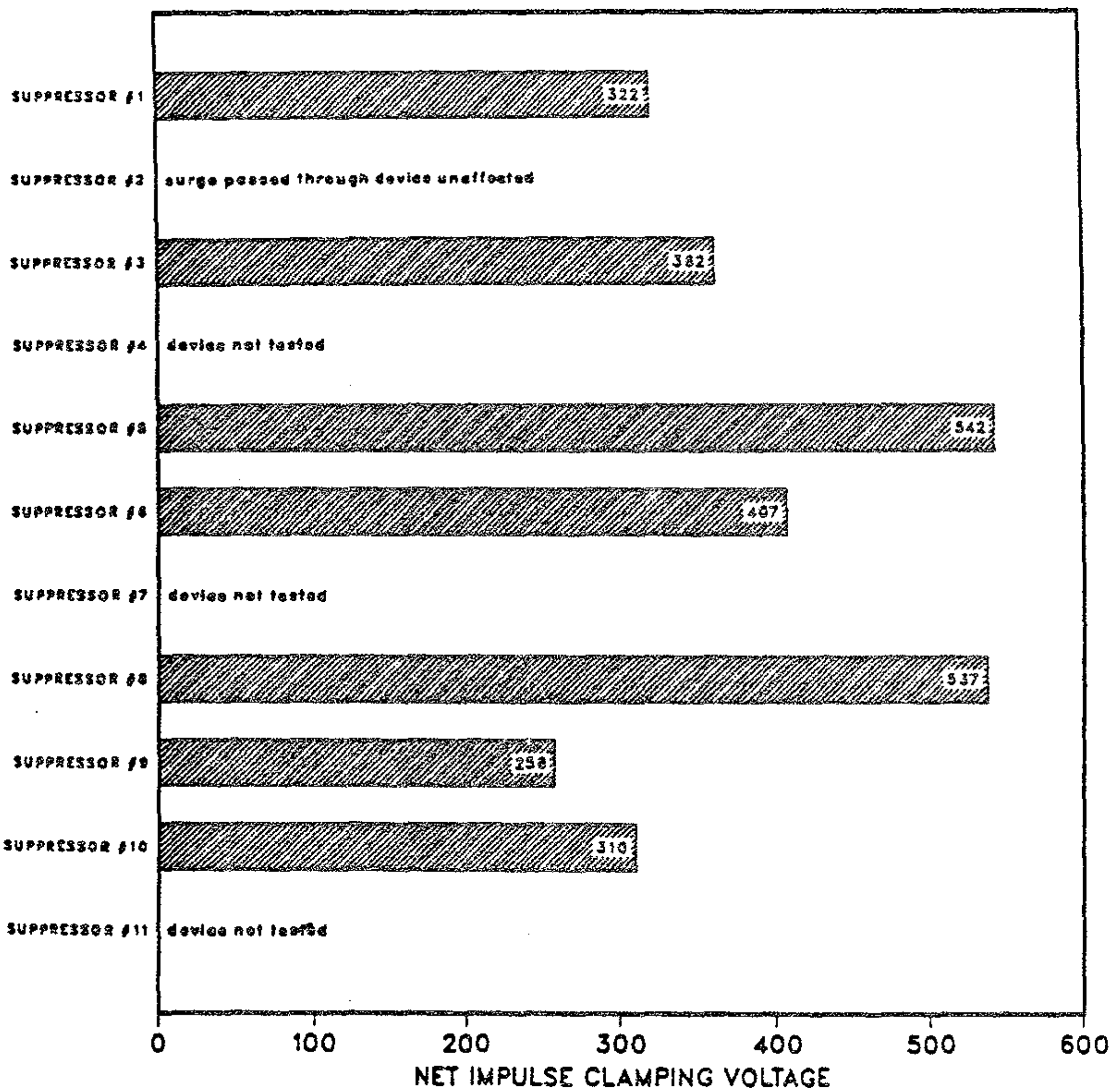


Fig. A-12. Neutral-to-ground voltage clamping levels of surge suppressors to a 1.0 kV common mode 1.2x50μs impulse.

Appendix B

Voltage Clamping Levels
of Power Conditioners and
Uninterruptible Power Systems

POWER CONDITIONING DEVICES

AND

UNINTERRUPTIBLE POWER SYSTEMS TESTED

1. Sola Constant Voltage Transformer, 500 VA sinusoidal output, ferroresonant transformer.

2. Topaz, model 91095-12, 500 VA isolation transformer.

3. Rapid Power Technologies, model FPSAAD50120:A, 500 VA ferroresonant transformer.

4. RTE Deltec, model MPC 560, 500 VA tap-changing power conditioner.

5. Stabiline SVRS88101CU, 1000 VA tap-changing voltage regulator.

6. Sola Constant Voltage Transformer, 120 VA normal-harmonic, ferroresonant transformer.

7. American Power Power Conversion, model 450 AT+, 450 VA uninterruptible power system.

Table 14. Commercial power conditioners, isolation transformers, and uninterruptible power systems tested for protection levels against impulse voltages measured in rural Alaska.

Normal Mode Ringwave

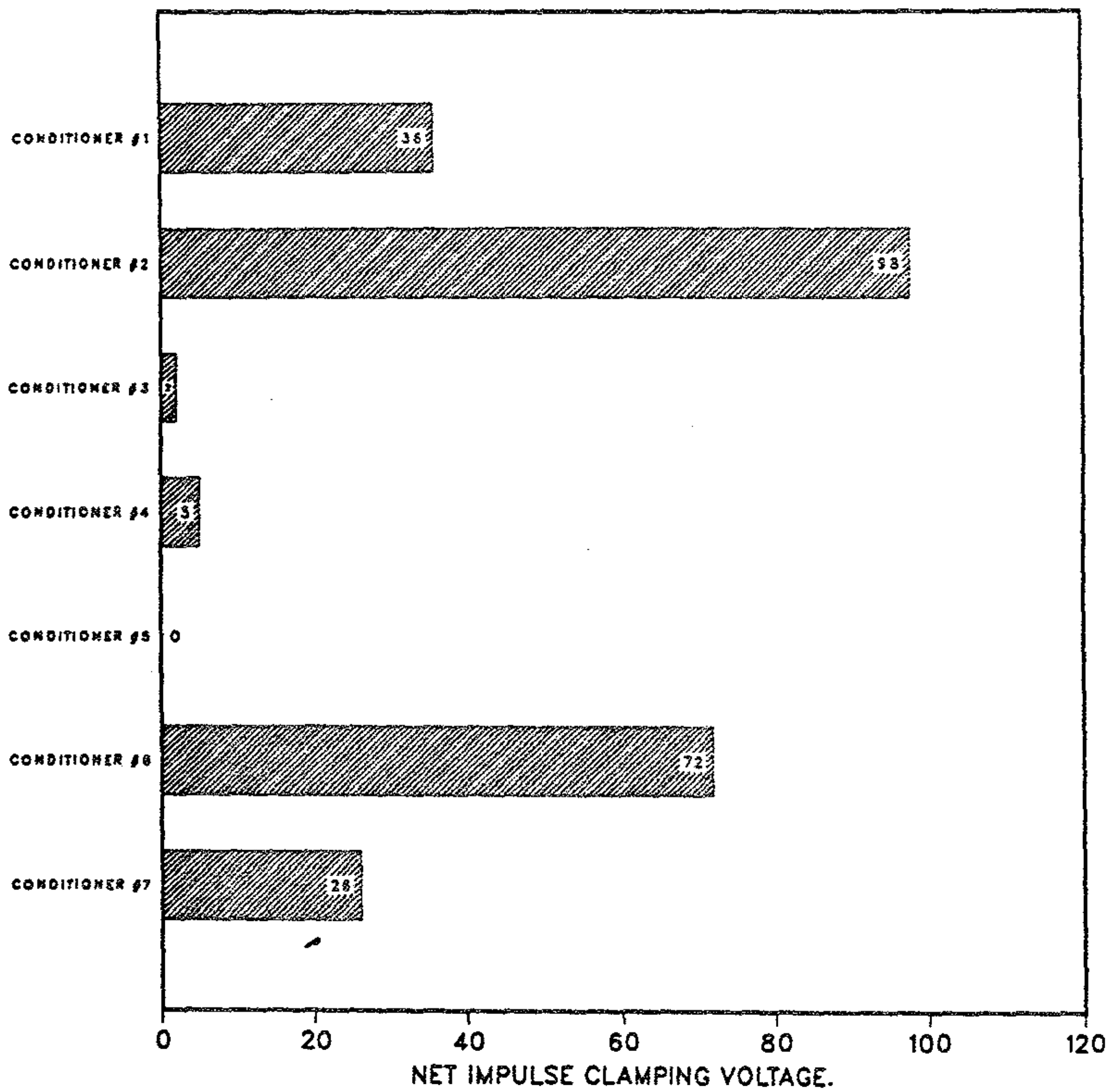


Fig. B-1. Line to neutral voltage clamping levels of various types of power conditioning devices to a 400 V normal mode oscillatory impulse.

Normal Mode Ringwave

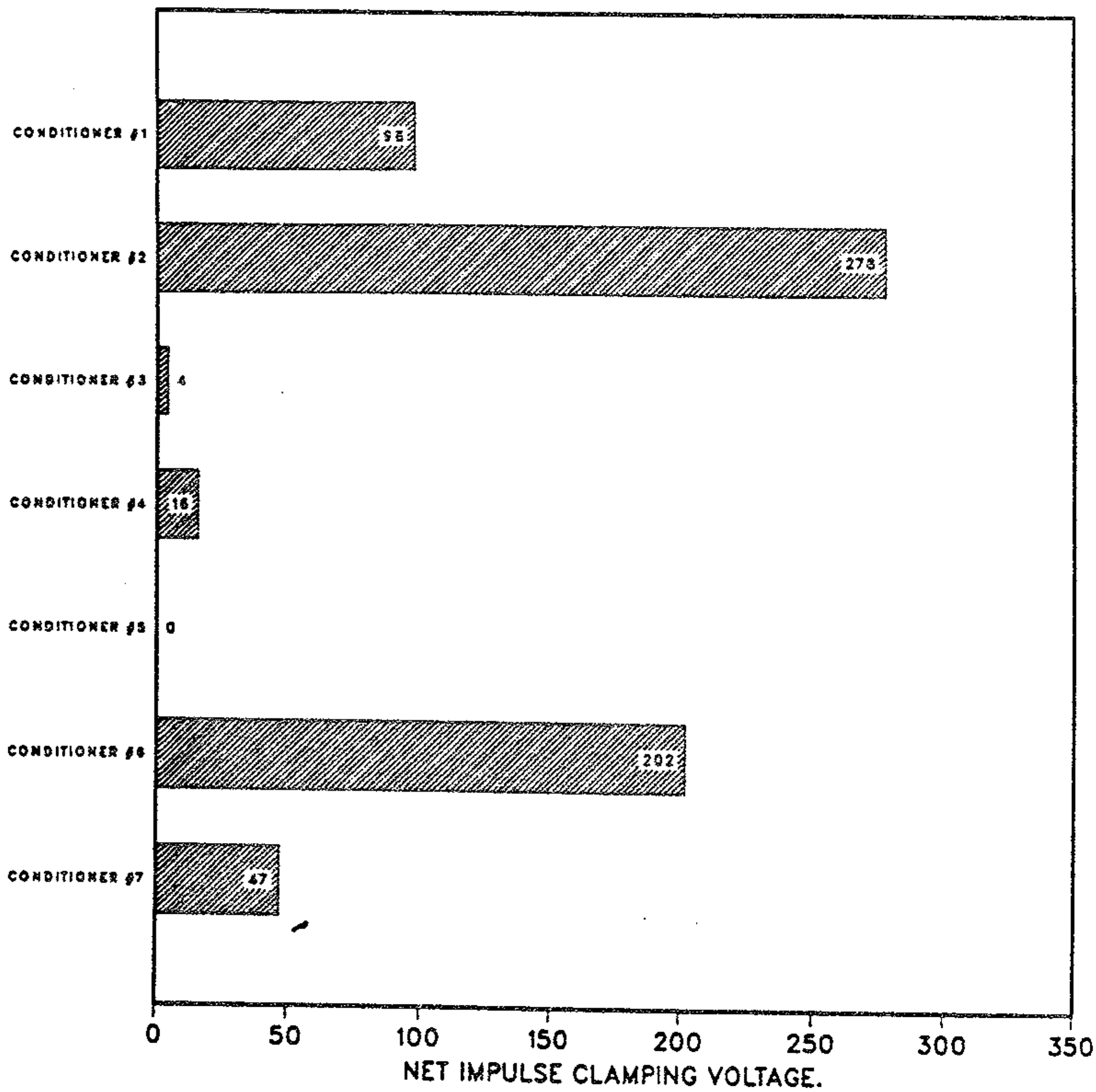


Fig. B-2. Line to neutral voltage clamping levels of various types of power conditioning devices to a 1.0 kV normal mode oscillatory impulse.

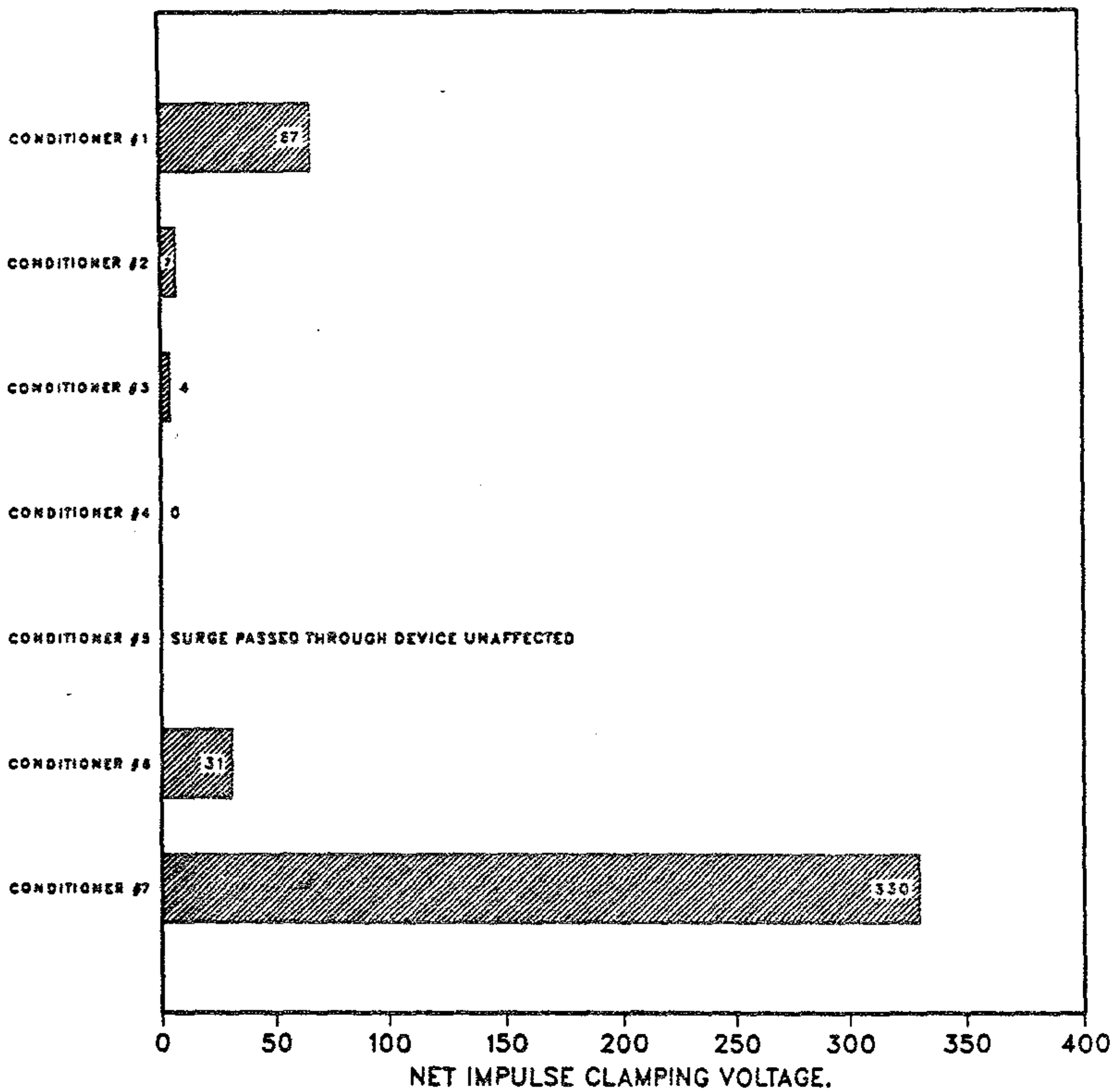


Fig. B-3. Line to ground voltage clamping levels of various types of power conditioning devices to a 400 V common mode oscillatory impulse.

Common Mode Ringwave

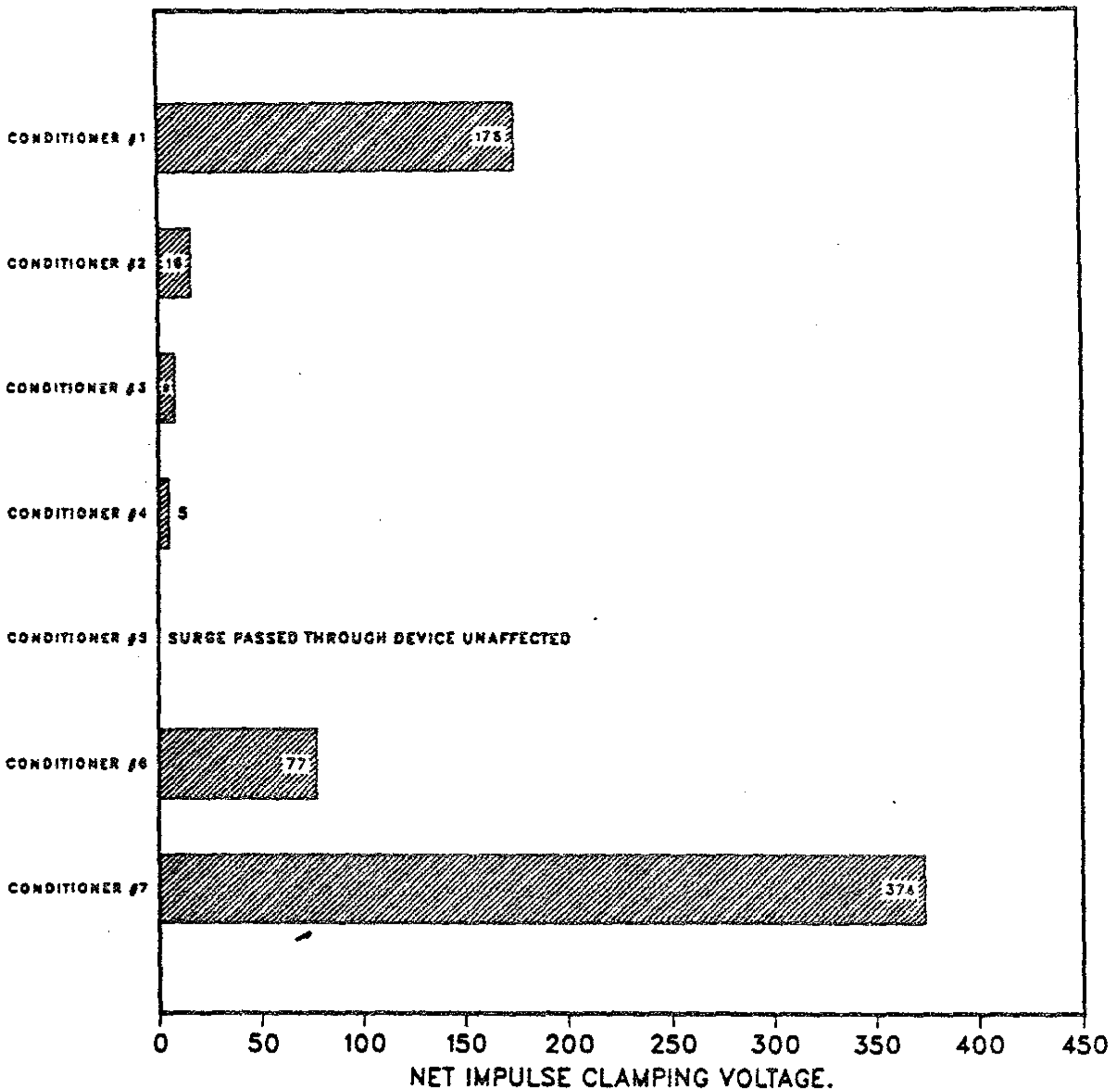


Fig. B-4. Line to ground voltage clamping levels of various types of power conditioning devices to a 1.0 kV common mode oscillatory impulse.

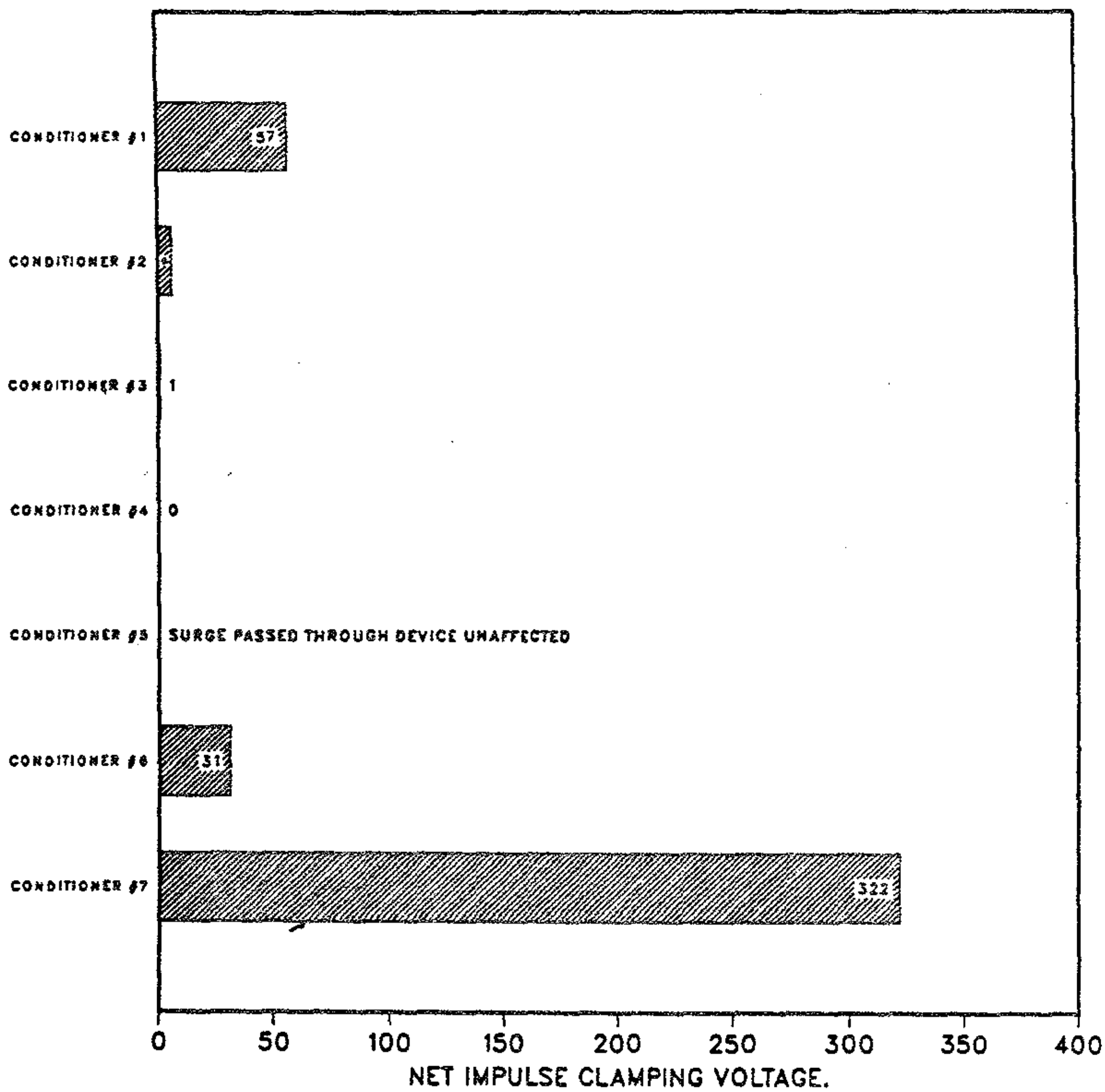


Fig. B-5. Neutral to ground voltage clamping levels of various types of power conditioning devices to a 400 V common mode oscillatory impulse.

Common Mode Ringwave

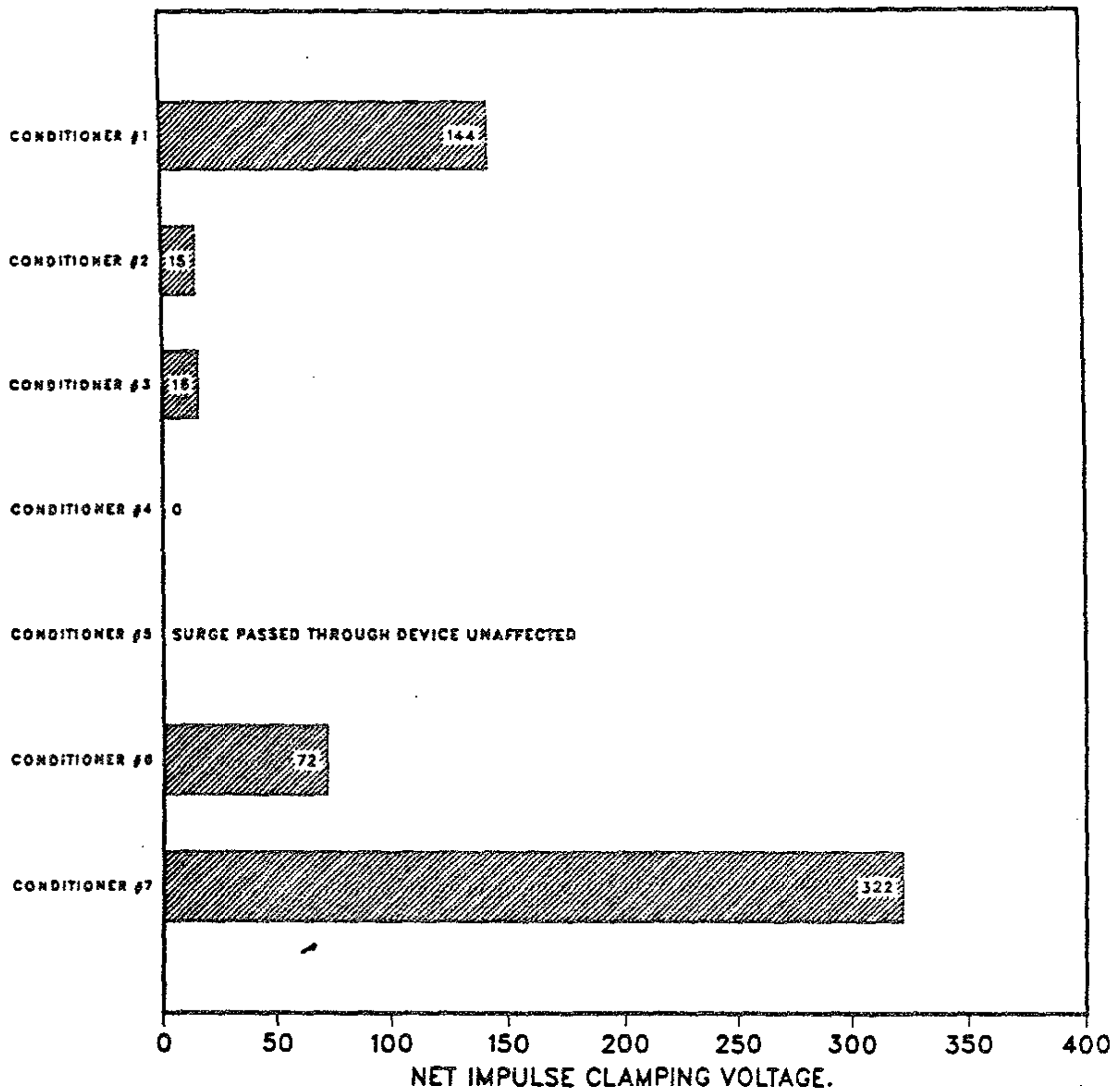


Fig. B-6. Neutral to ground voltage clamping levels of various types of power conditioning devices to a 1.0 kV common mode oscillatory impulse.

Normal Mode Unipolar Impulse

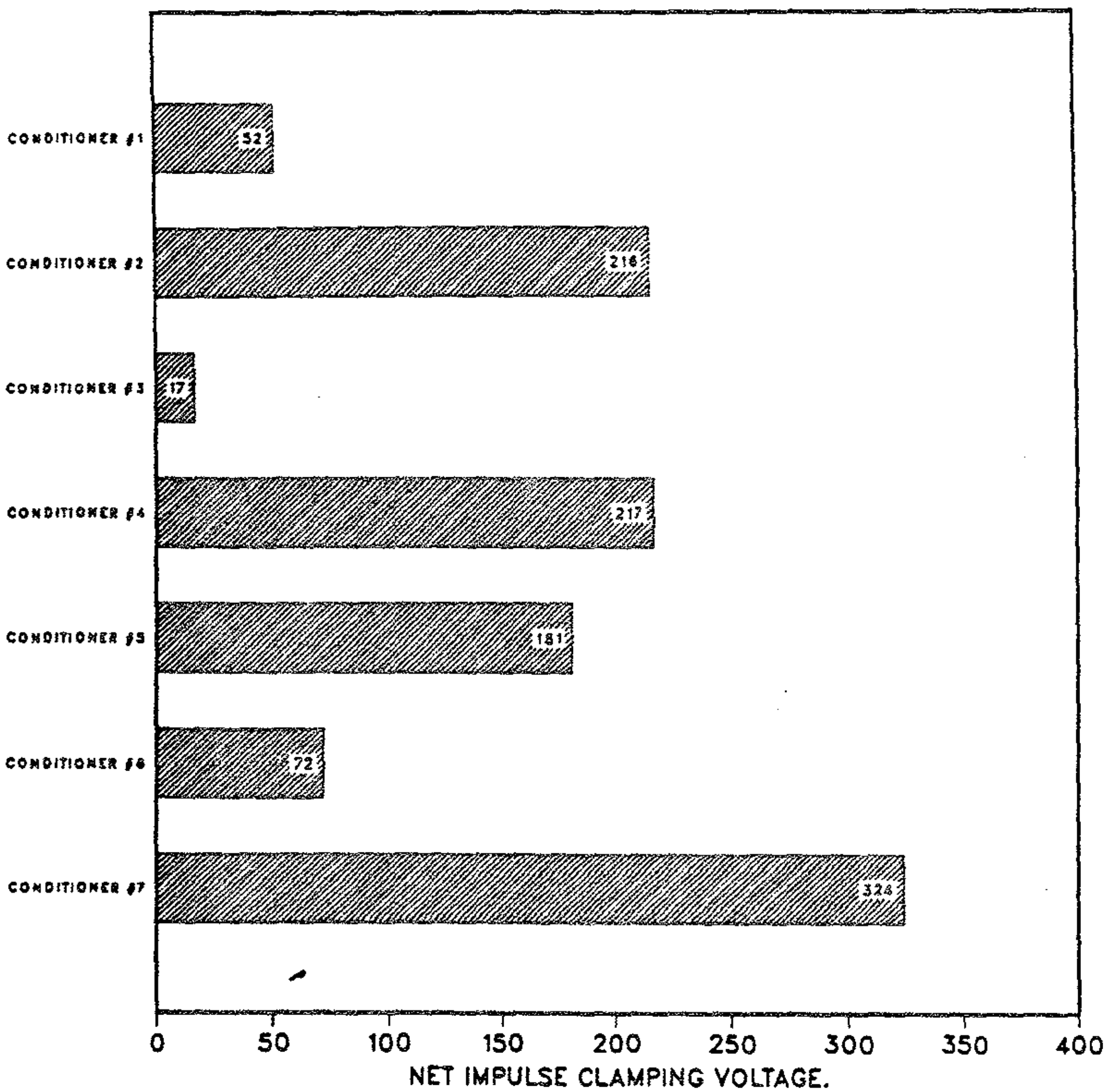


Fig. B-7. Line to neutral voltage clamping levels of various types of power conditioning devices to a 400 V normal mode 1.2x50μs impulse.

Normal Mode Unipolar Impulse

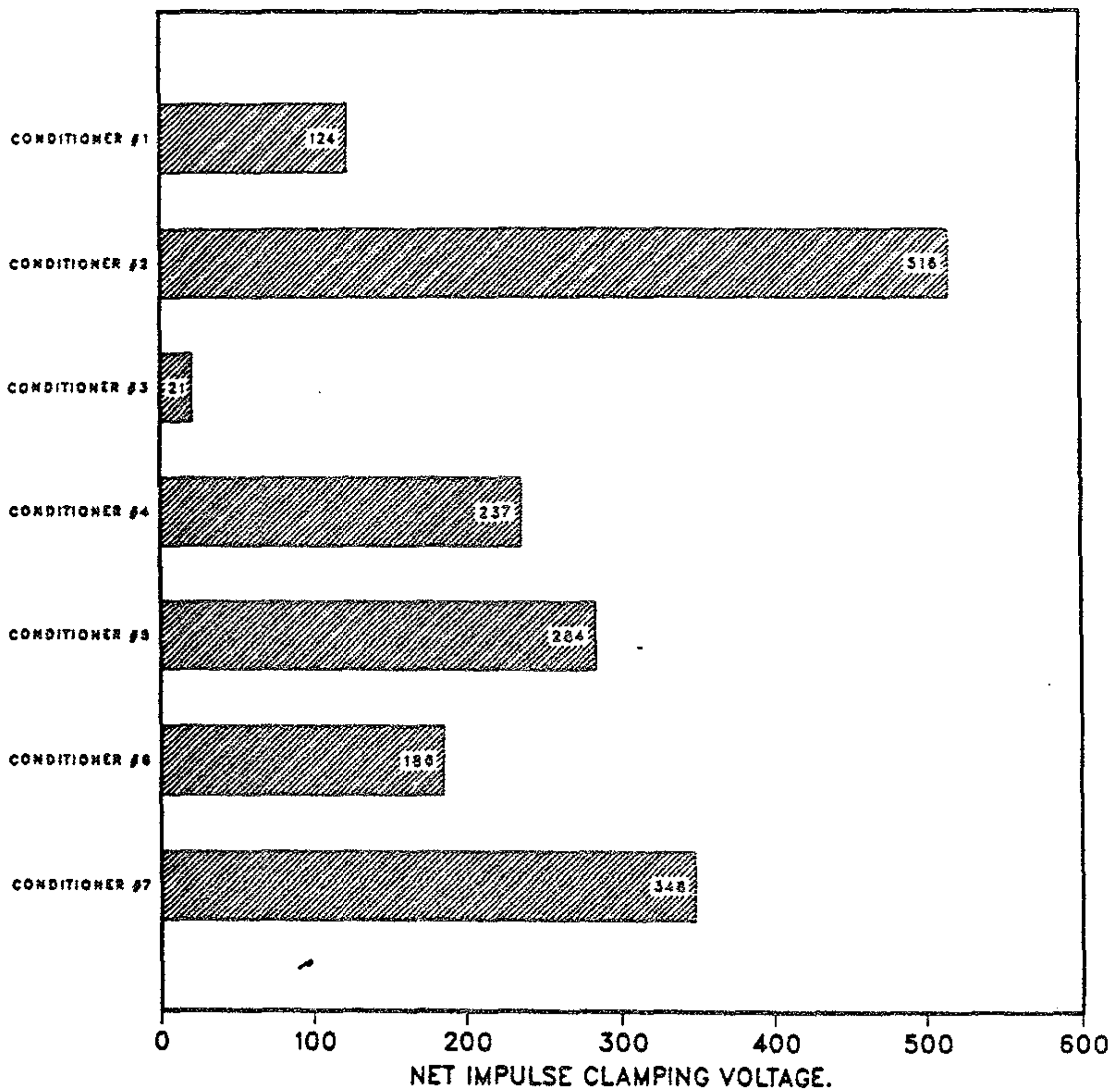


Fig. B-8. Line to neutral voltage clamping levels of various types of power conditioning devices to a 1.0 kV normal mode 1.2x50μs impulse.

Common Mode Unipolar Impulse

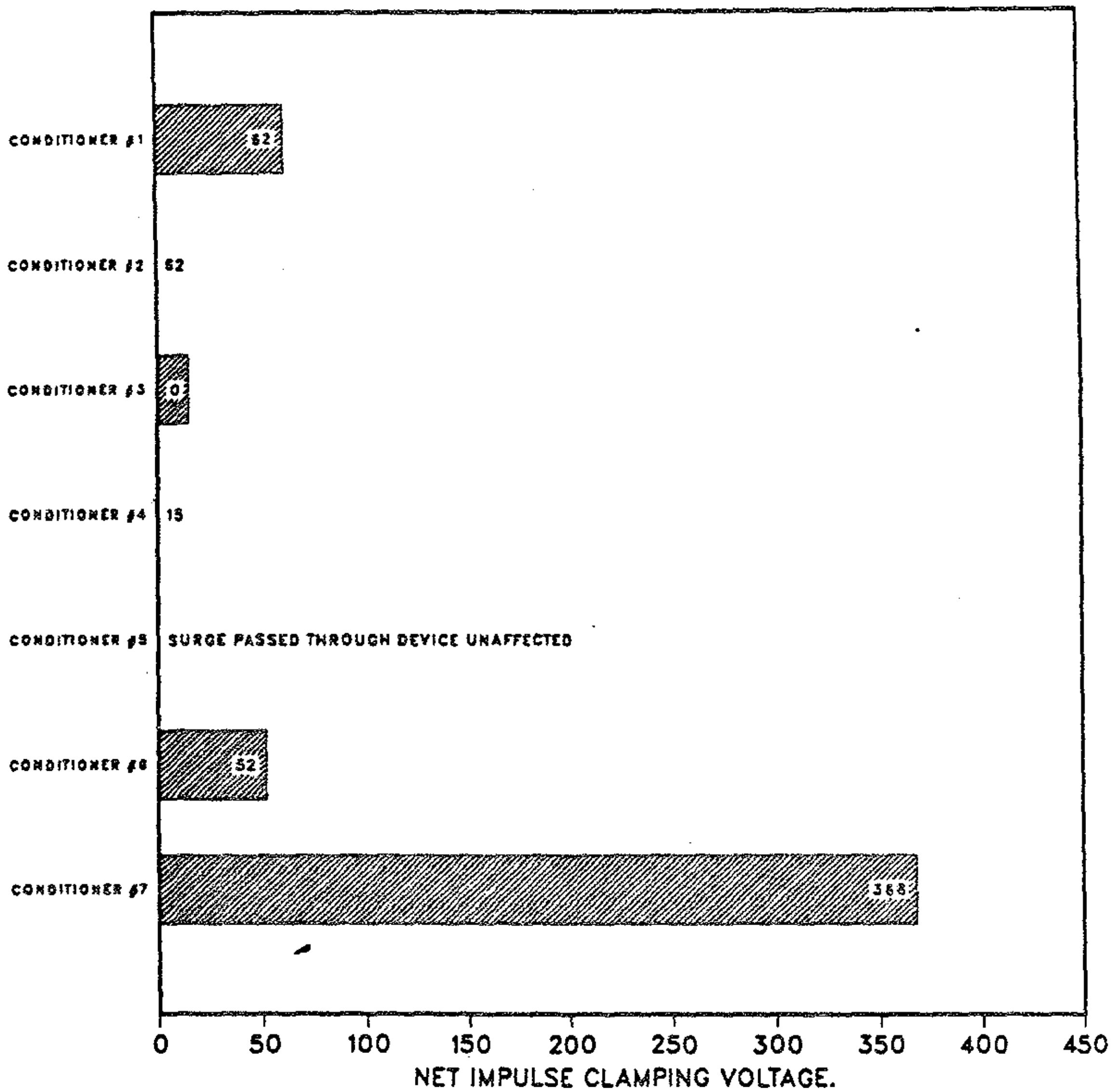


Fig. B-9. Line to ground voltage clamping levels of various types of power conditioning devices to a 400 V common mode 1.2x50μs impulse.

Common Mode Unipolar Impulse

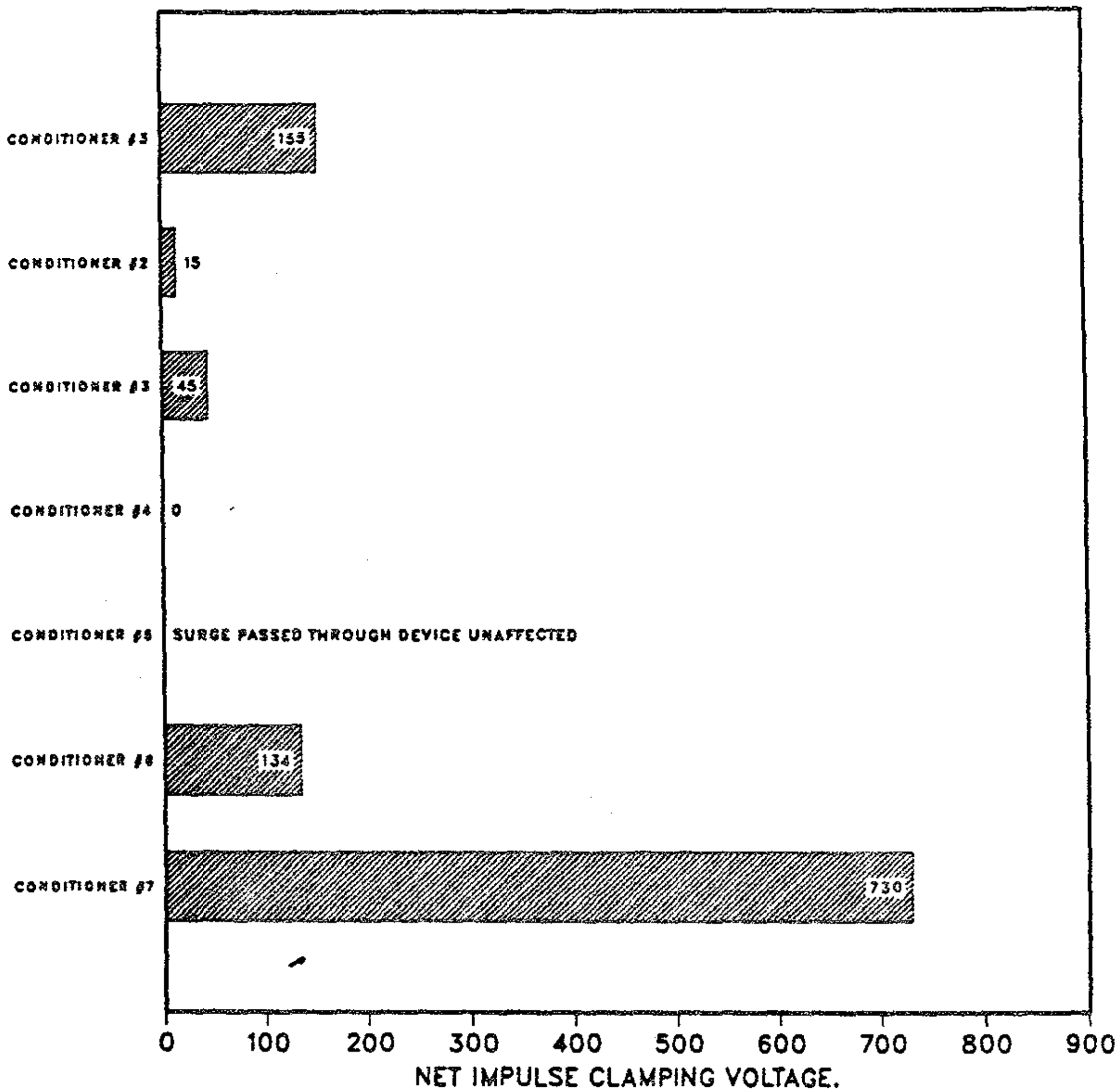


Fig. B-10. Line to ground voltage clamping levels of various types of power conditioning devices to a 1.0 kV common mode 1.2x50μs impulse.

Common Mode Unipolar Impulse

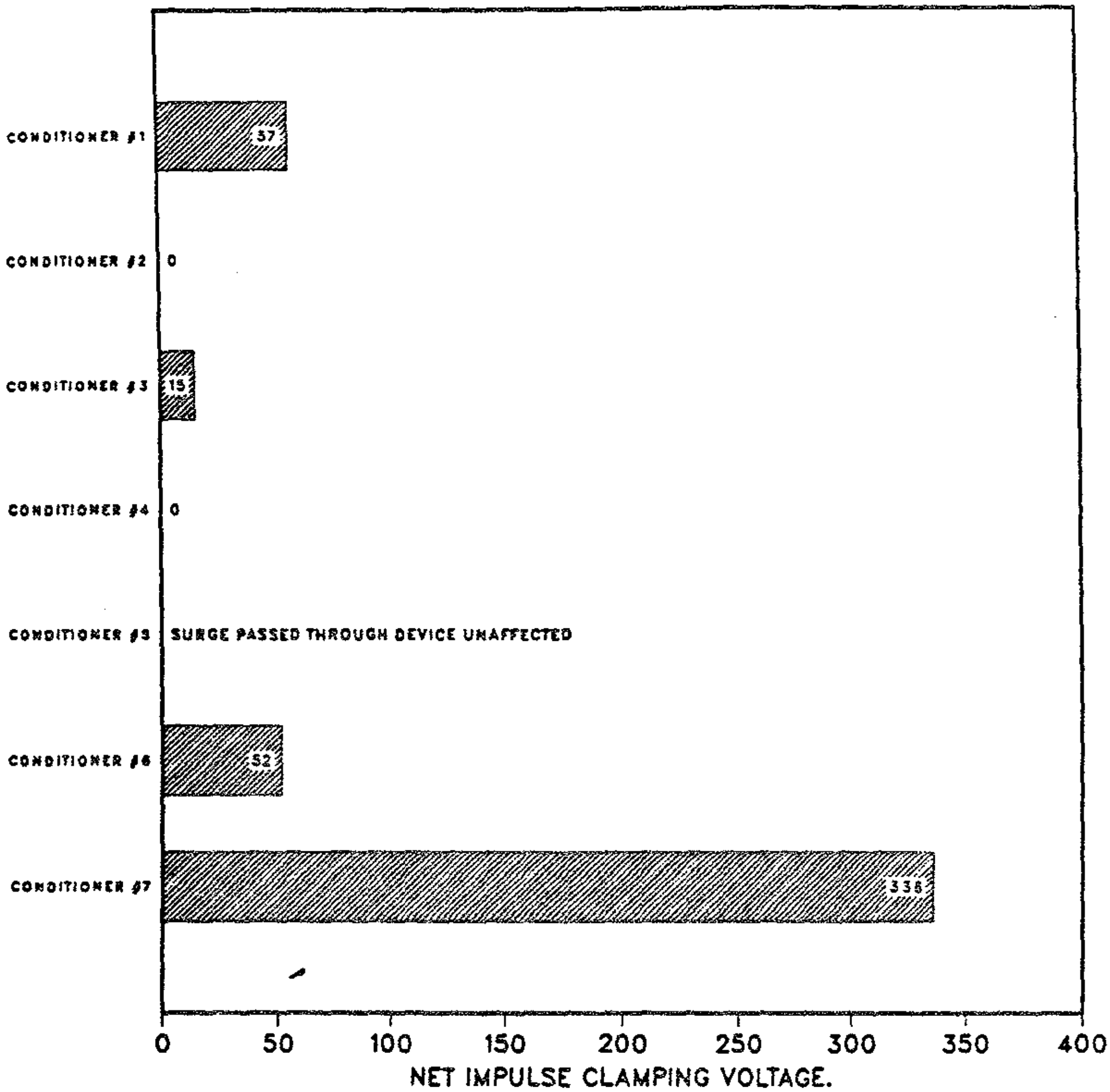


Fig. B-11. Neutral to ground voltage clamping levels of various types of power conditioning devices to a 400 V common mode 1.2x50μs impulse.

Common Mode Unipolar Impulse

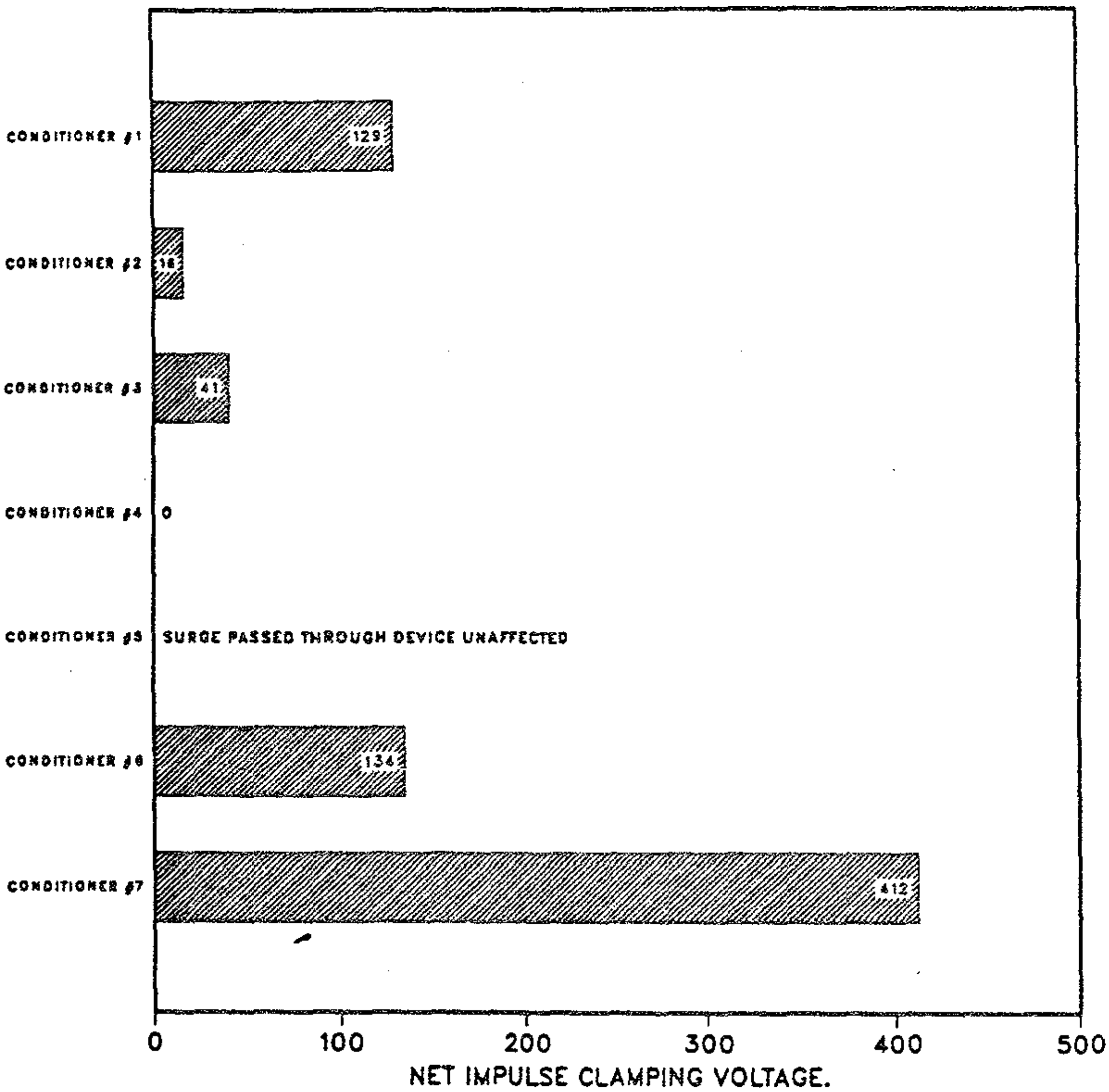


Fig. B-12. Neutral to ground voltage clamping levels of various types of power conditioning devices to a 1.0 kV common mode $1.2 \times 50 \mu s$ impulse.

Appendix C

Noise Suppression of Surge Suppressors and Power Conditioners

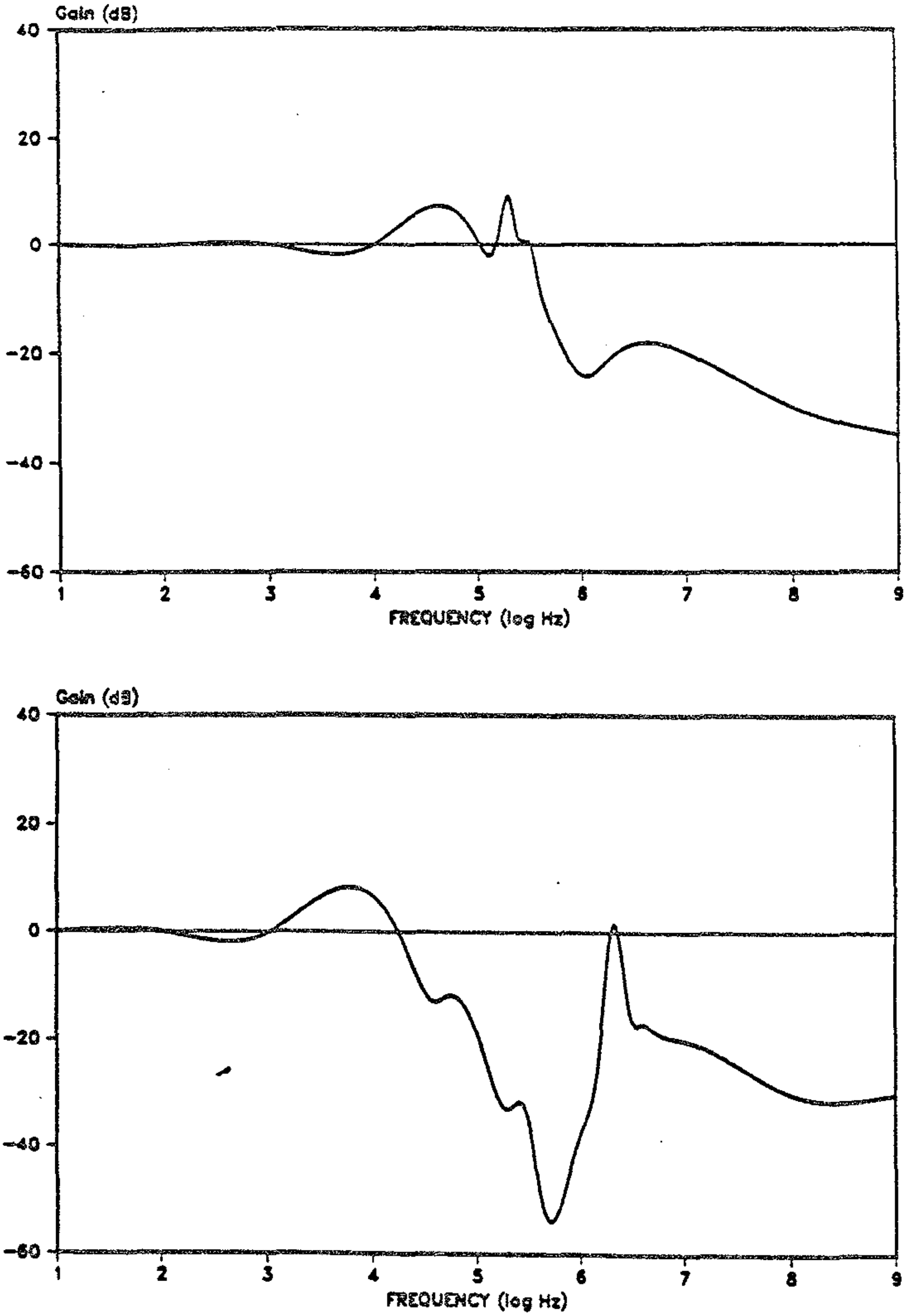


Figure C-1. Normal mode noise attenuation of surge suppressor EMI/RFI filters. Top: Isobar IB-4. Bottom: Microage EFI-453 Turbo-ST (bottom). Note: The x-axis label represents the base ten logarithm of the corresponding noise frequency. The frequency can be obtained using $F = 10^N$, for N= 1,2,3,4, etc.

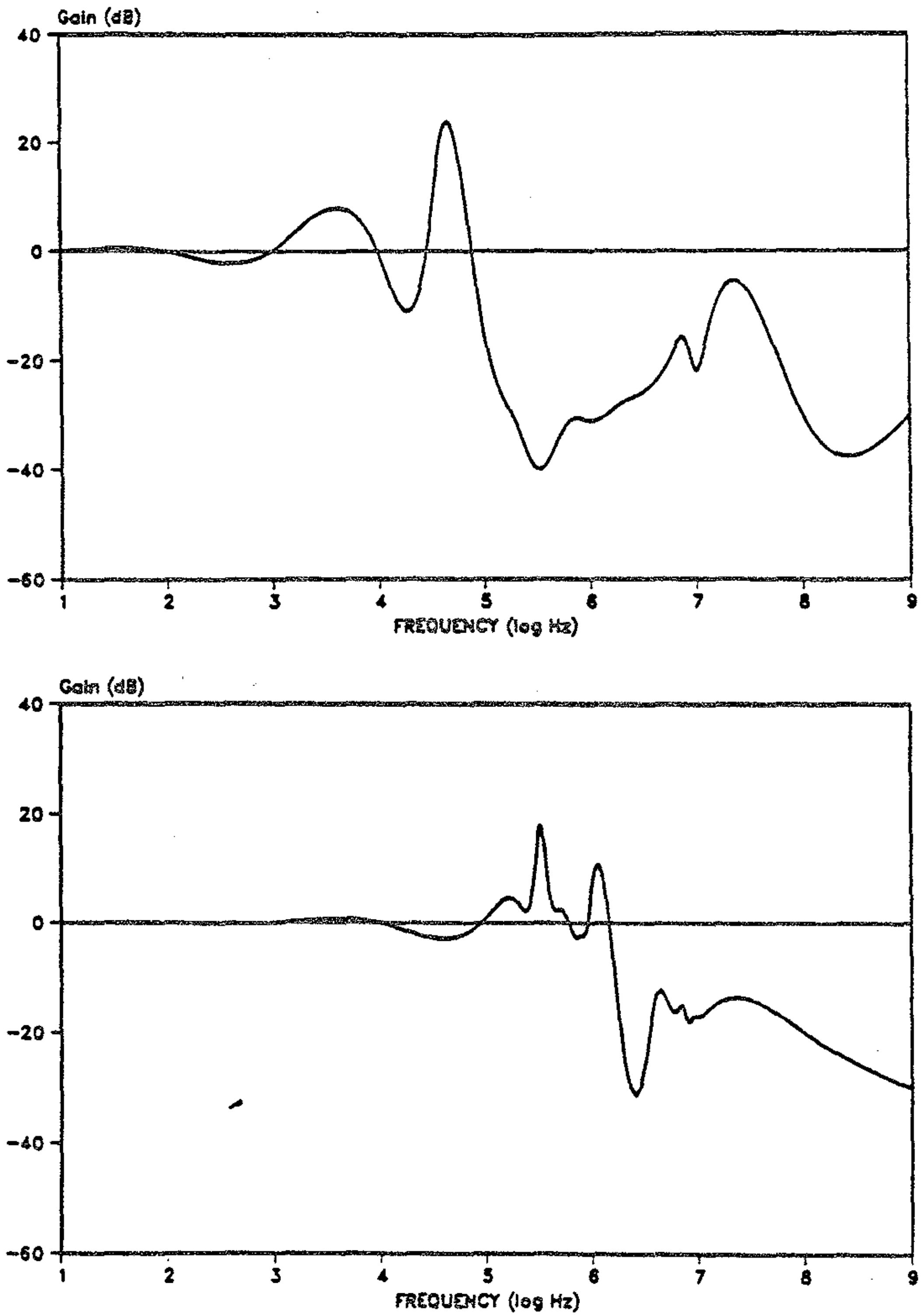


Figure C-2. Normal mode noise attenuation of surge suppressor EMI/RFI filters. Top: SL Waber Datagard 315S. Bottom: Curtis Ruby.

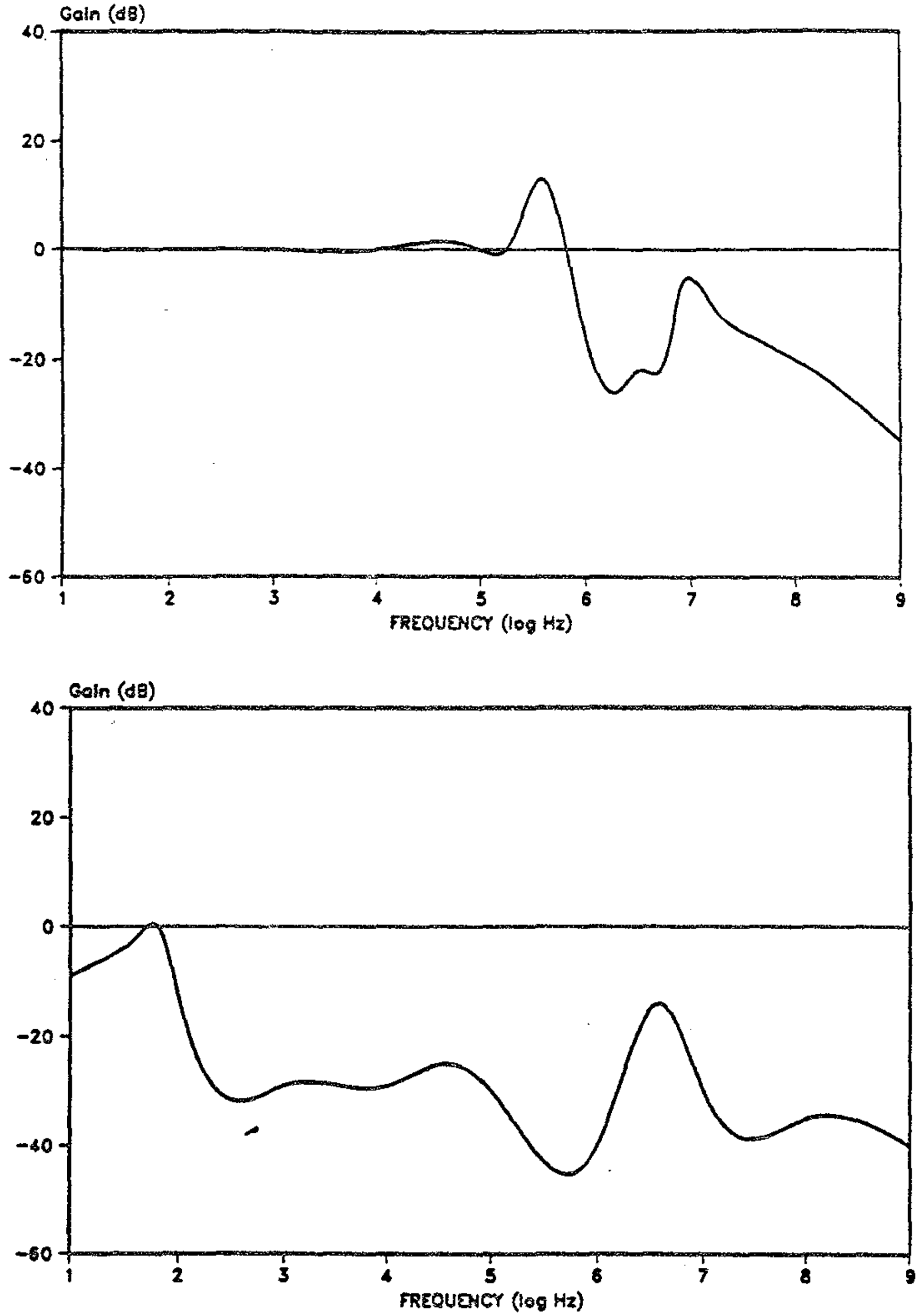
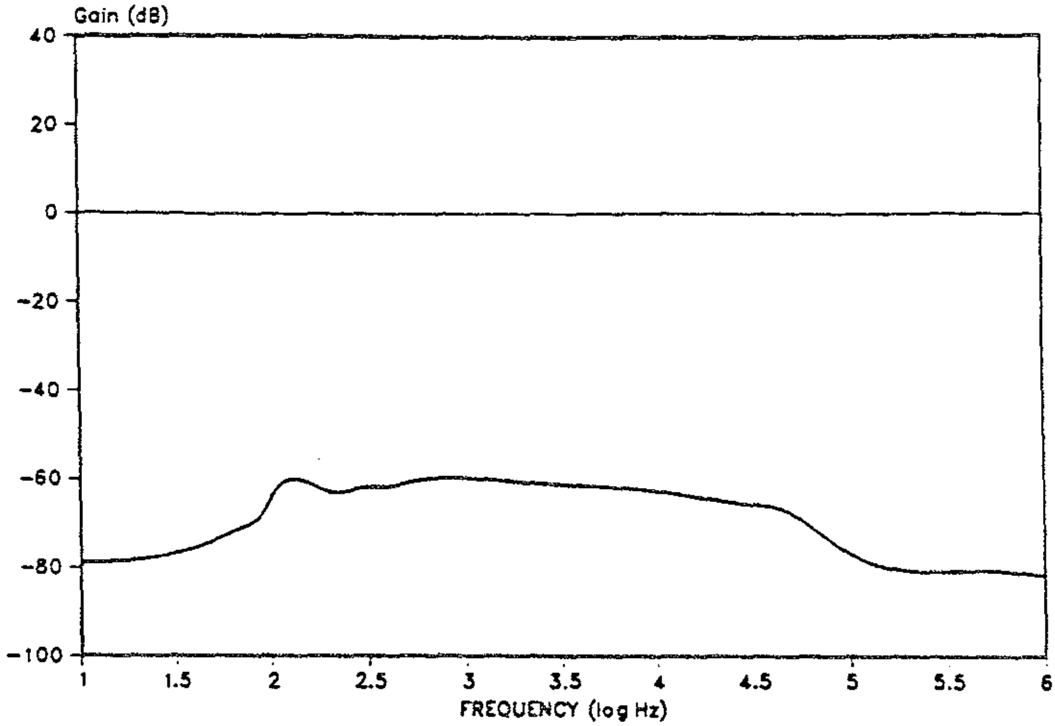


Figure C-3. Top: Normal mode noise attenuation of EMI/RFI filter of SL Waber Datagard DG204 surge suppressor. Bottom: Normal mode noise attenuation of Rapid 500 VA ferroresonant transformer.



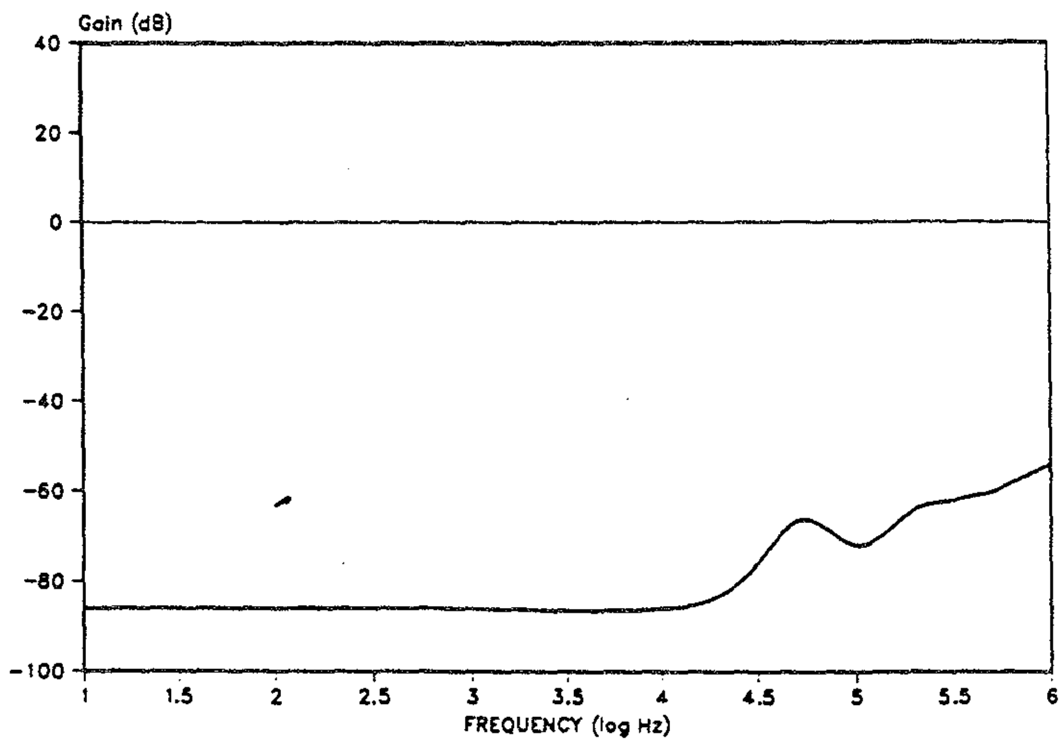


Figure C-4. Top: Common mode noise attenuation of GE model no. 9T56Y4324 600 VA transformer. Bottom: Common mode noise attenuation of RTE Deltec 500 VA tap changing power conditioner.

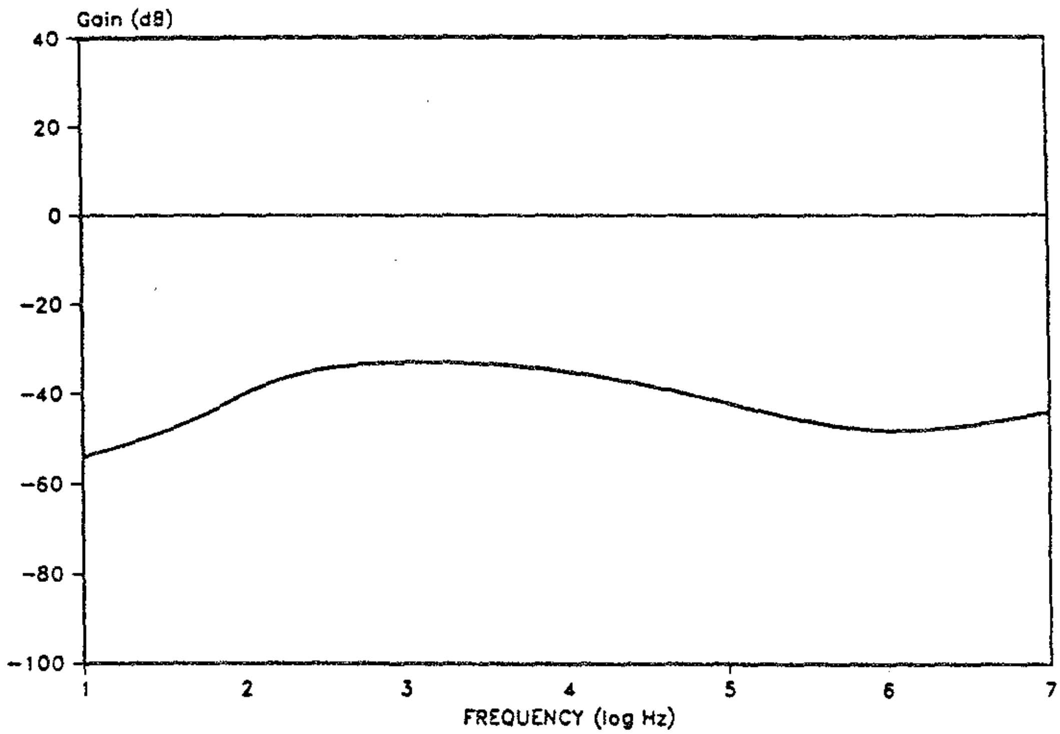


Figure C-5. Common mode noise attenuation of a Topaz 500 VA Isolation transformer.

Appendix D

Waveforms and Regulating Characteristics
of
Power Conditioners and
Uninterruptible Power Systems

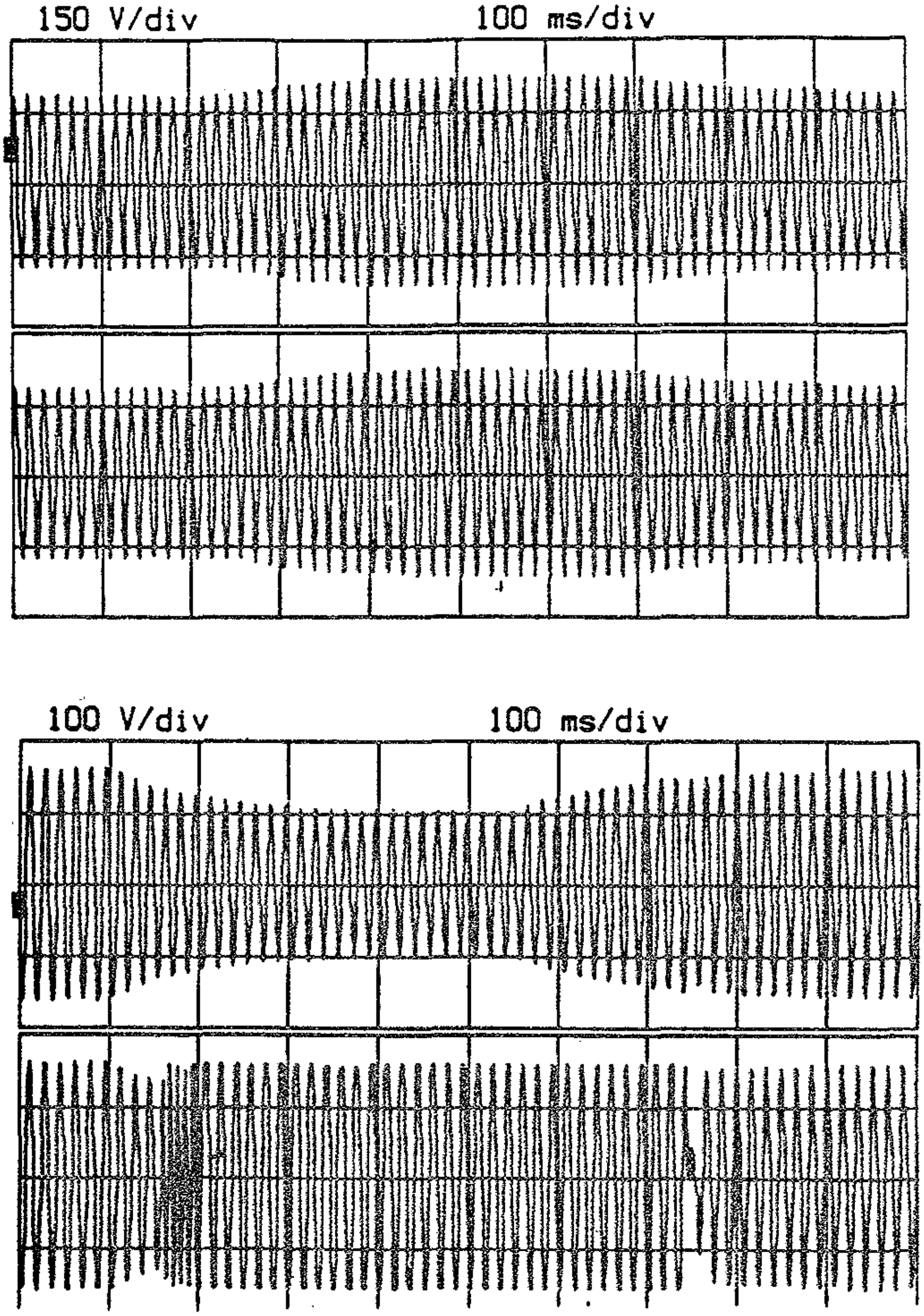
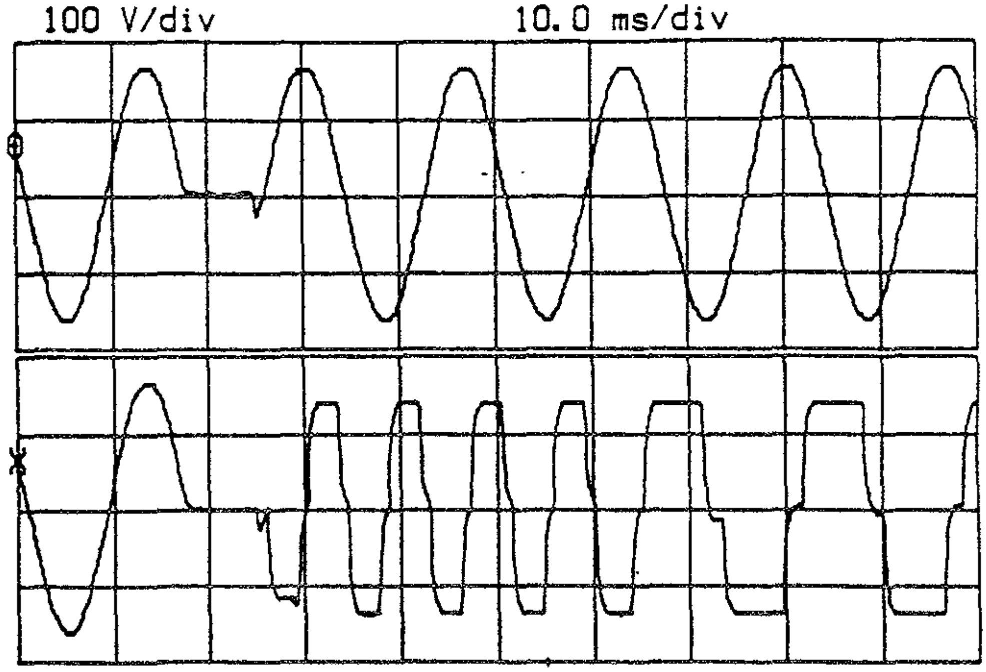


Figure D-1. Top: Cuesta DS 200 uninterruptible power system passes short term voltage surge of 150 V_{rms}, typical of many small UPS systems. Bottom: DS 200 switches on inverter to in response to a deep voltage sag of 71 V_{rms}.



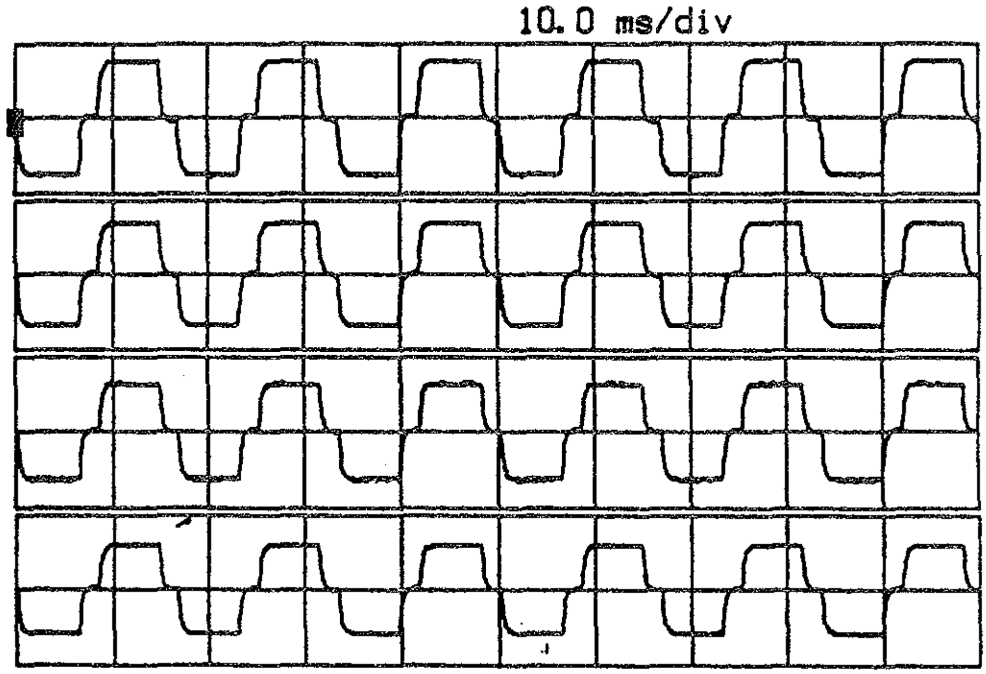


Figure D-2. Top: Cuesta DS 200 uninterruptible power system triggering inverter in response to 1/2 cycle voltage drop. The unit synchronizes with the power system and shuts off inverter between 0.1 and 0.25 seconds after normal system voltage resumes. Bottom: DS 200 inverter output under varying resistive loads of 50 W , 100 W, 150 W and 200 W.

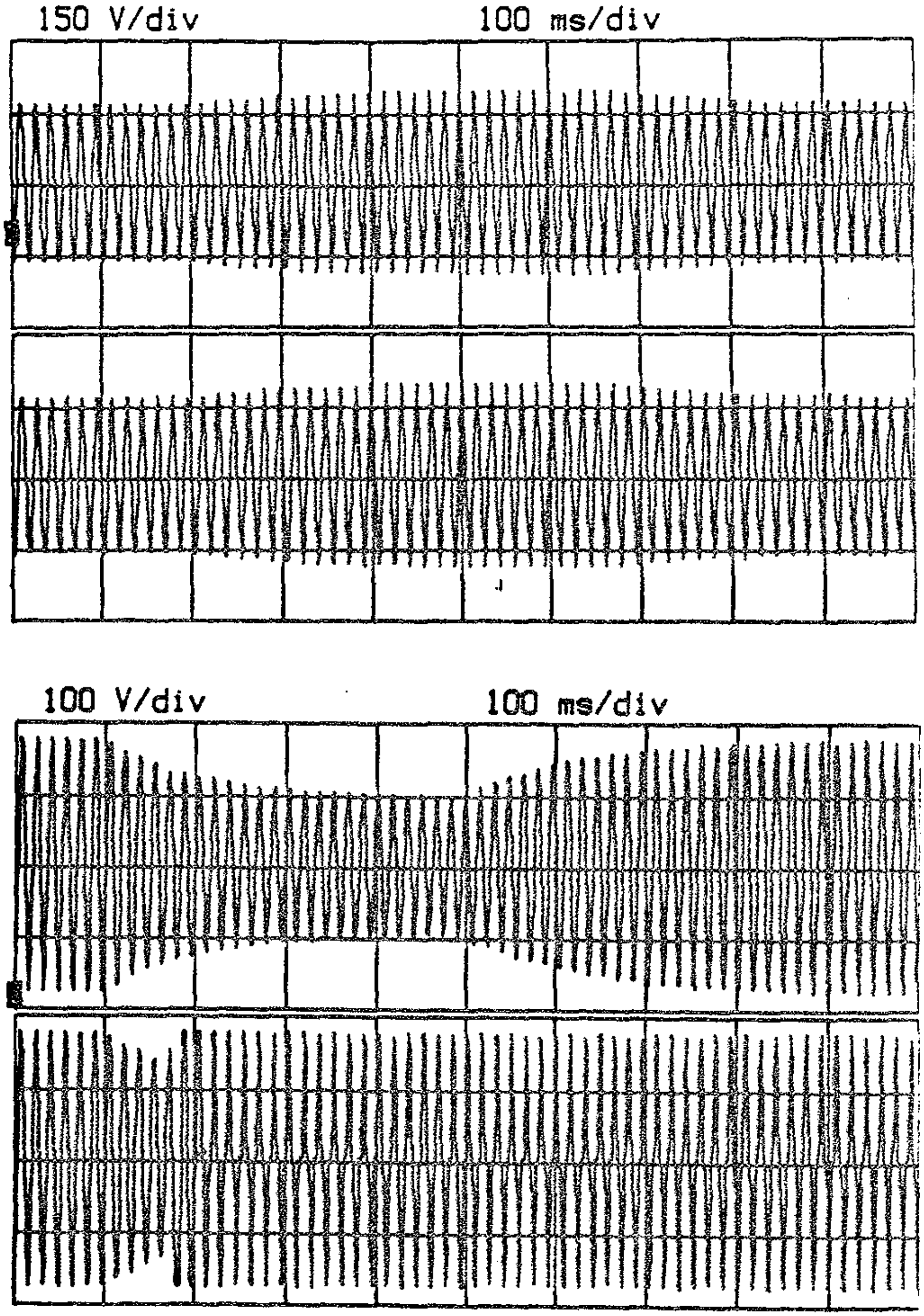


Figure D-3. Top: American Power Conversion 450 AT$^+$ UPS passes overvoltage of 150 V_{rms}. Bottom: The same UPS switched on the inverter in response to a deep sagging voltage of 71 V_{rms}. The unit synchronizes after 1 second following return of normal system voltage.

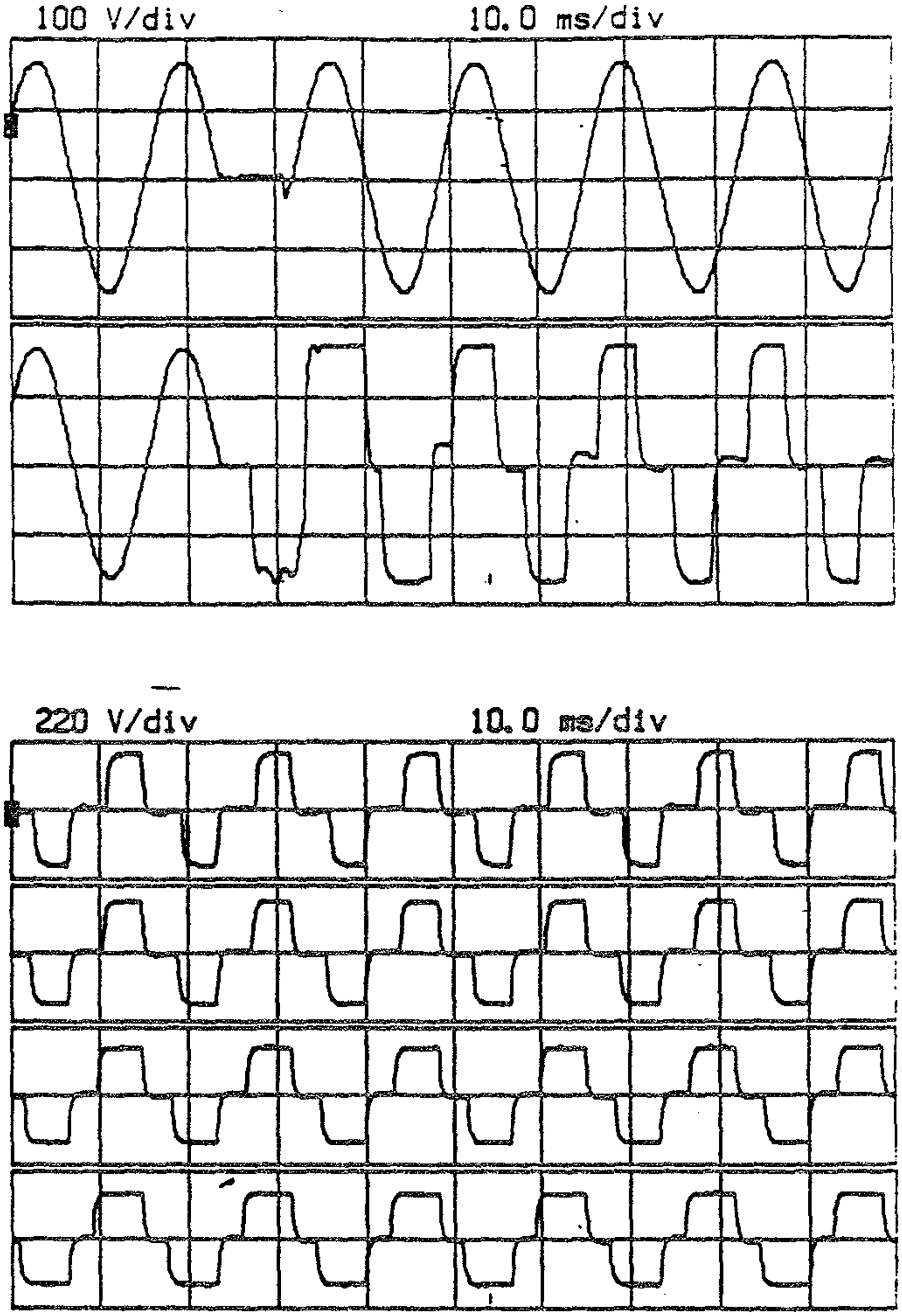


Figure D-4. American Power Conversion 450 AT+ UPS switches on inverter in response to the 1/2 cycle voltage drop. Bottom: The 450 AT+ inverter output under varying resistive loads of 75 W, 150 W, 225 W and 300 W.

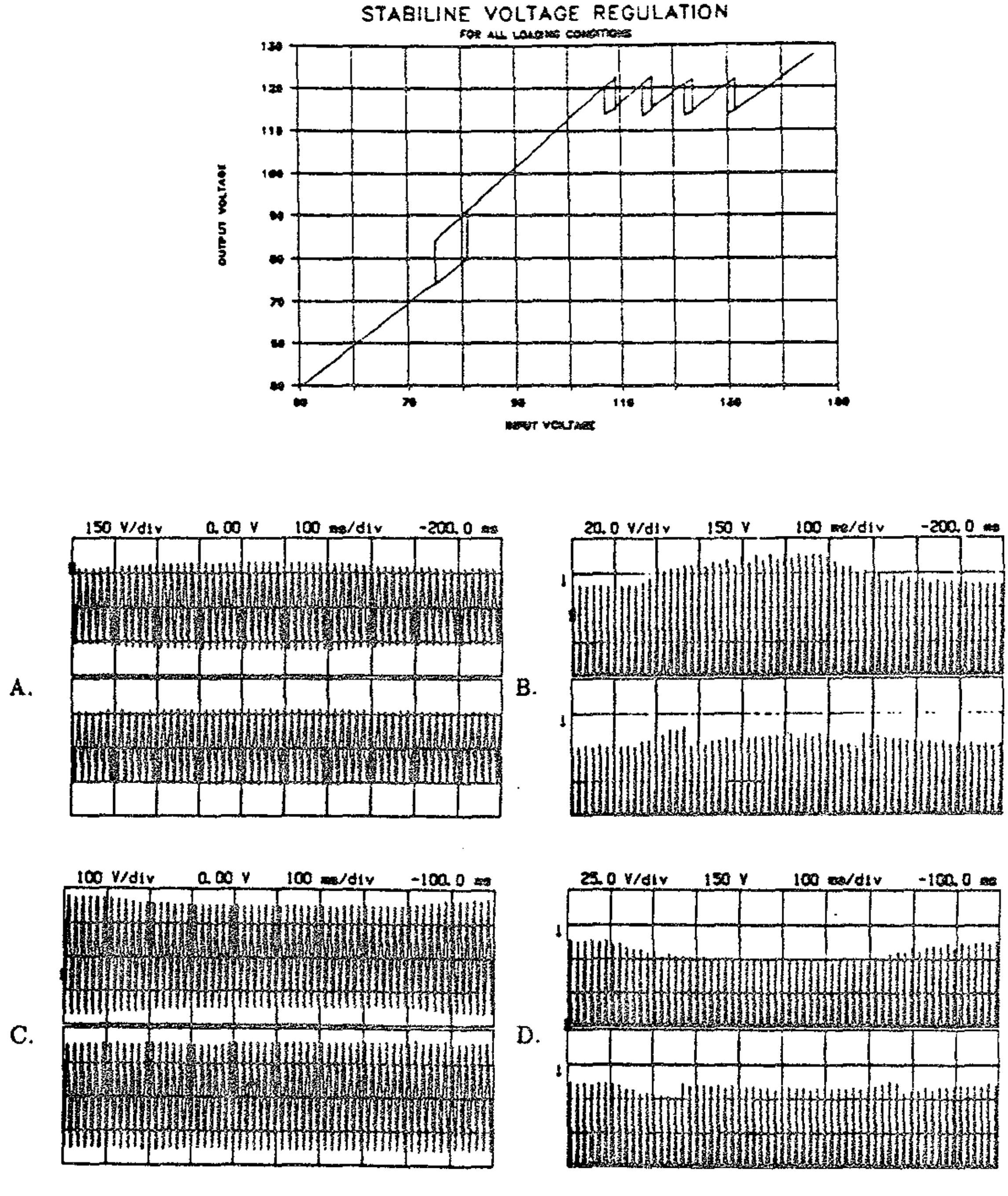


Figure D-5. Top: Stabiline 1000 VA tap changing voltage regulator output characteristics. A) Output holds at 123 V_{rms} for a voltage surge to 140 V_{rms}. B) First high voltage tap switches as surge exceeds 130 V_{rms}. C) Output holds nominally at 120 V_{rms} as input sags to 100 V_{rms}. D) First low voltage tap switches as sag reaches 114 V_{rms}.

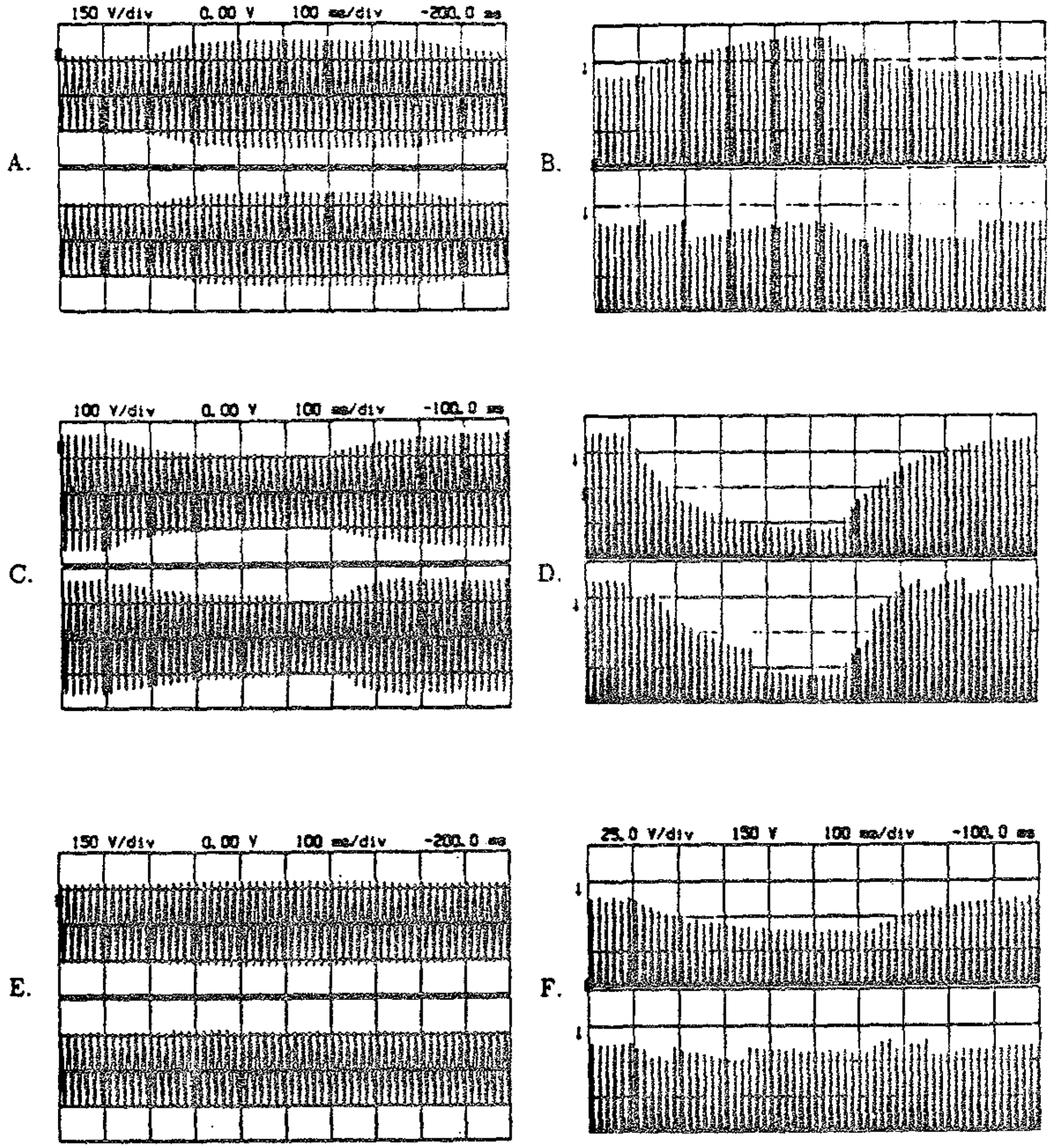


Figure D-6. Stabiline voltage regulator outputs. A) Surge to 170 V_{rms} is limited to 141 V_{rms} at regulator output. B) Surge to 136 V_{rms} triggers both high voltage taps. C) Response to sagging input voltage to 71 V_{rms}. D) Response to sagging input voltage to 65 V_{rms}. voltage taps switch in response to voltage sag to 70 V_{rms}. E) Output holds at 115 V_{rms} for steady overvoltage of 130 V_{rms}. F) Two low-voltage taps are switched during sagging voltage to 100 V_{rms}.

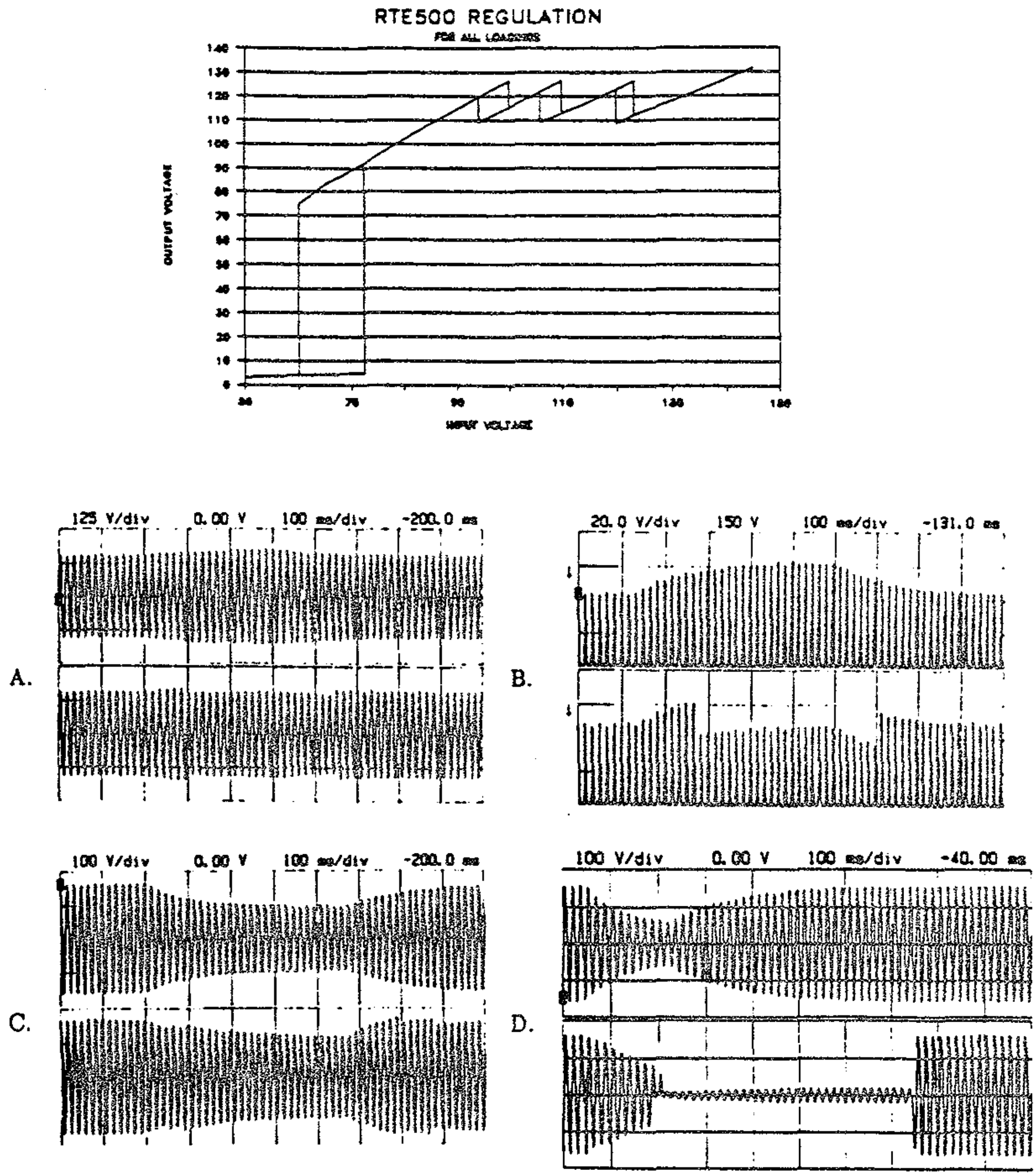
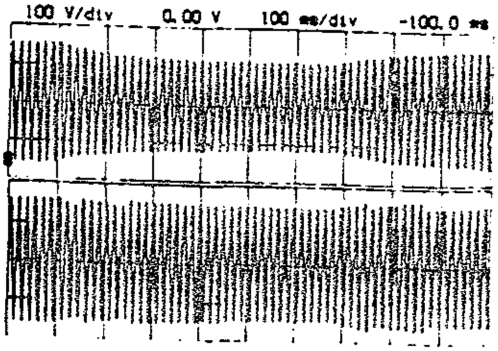


Figure D-7. Top: RTE Deltec 500 VA tap changing power conditioner output characteristics. A) The high voltage tap is switched as input voltage exceeds 125 V_{rms}. B) Magnified oscillogram of high voltage tap switching. C) Output voltage drops to 81 V_{rms} as input voltage sags to 67 V_{rms}. D) Severe voltage sag to 30 V_{rms} switches lowest tap end essentially removes power to the load.

A.



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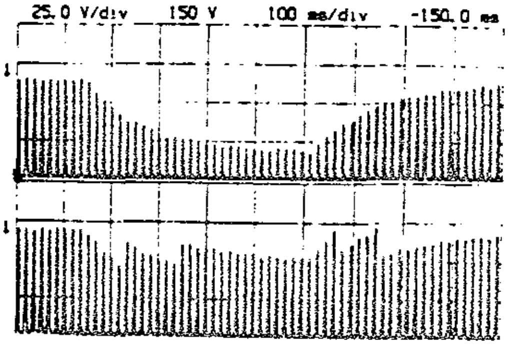
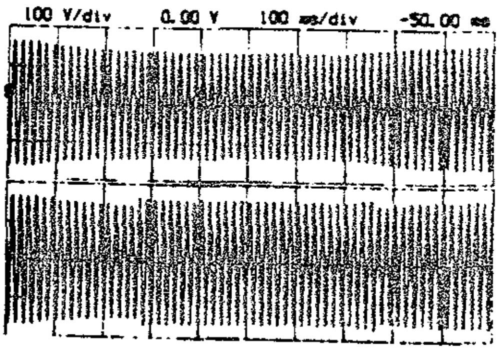
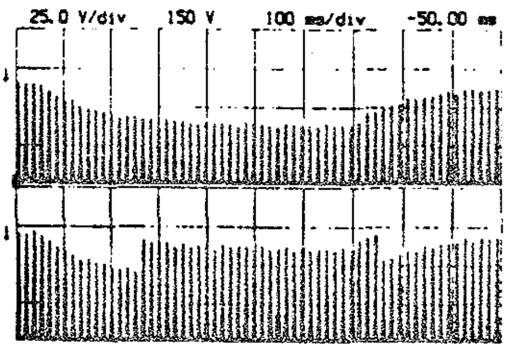


C.



D.



E.

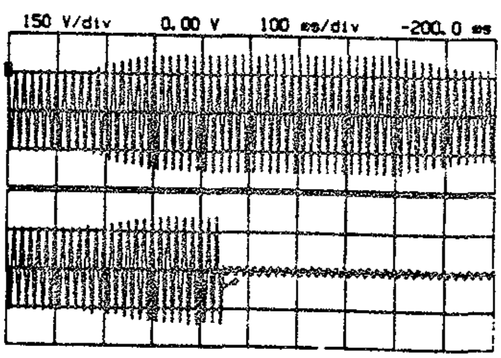


Figure D-8. RTE Deltec power conditioner outputs. A) Output voltage drops to 115 V_{rms} as the input sags to 85 V_{rms} at 1/2 load. B) Magnified oscillogram of the switching of the first two low voltage taps during a sag to 85 V_{rms}. C) First low voltage tap is switched as input voltage sags below 100 V_{rms}. D) Magnified oscillogram of the first low voltage tap switching in response to an input sag to 100 V_{rms}. E) Surge to 152 volts removes load from power source.

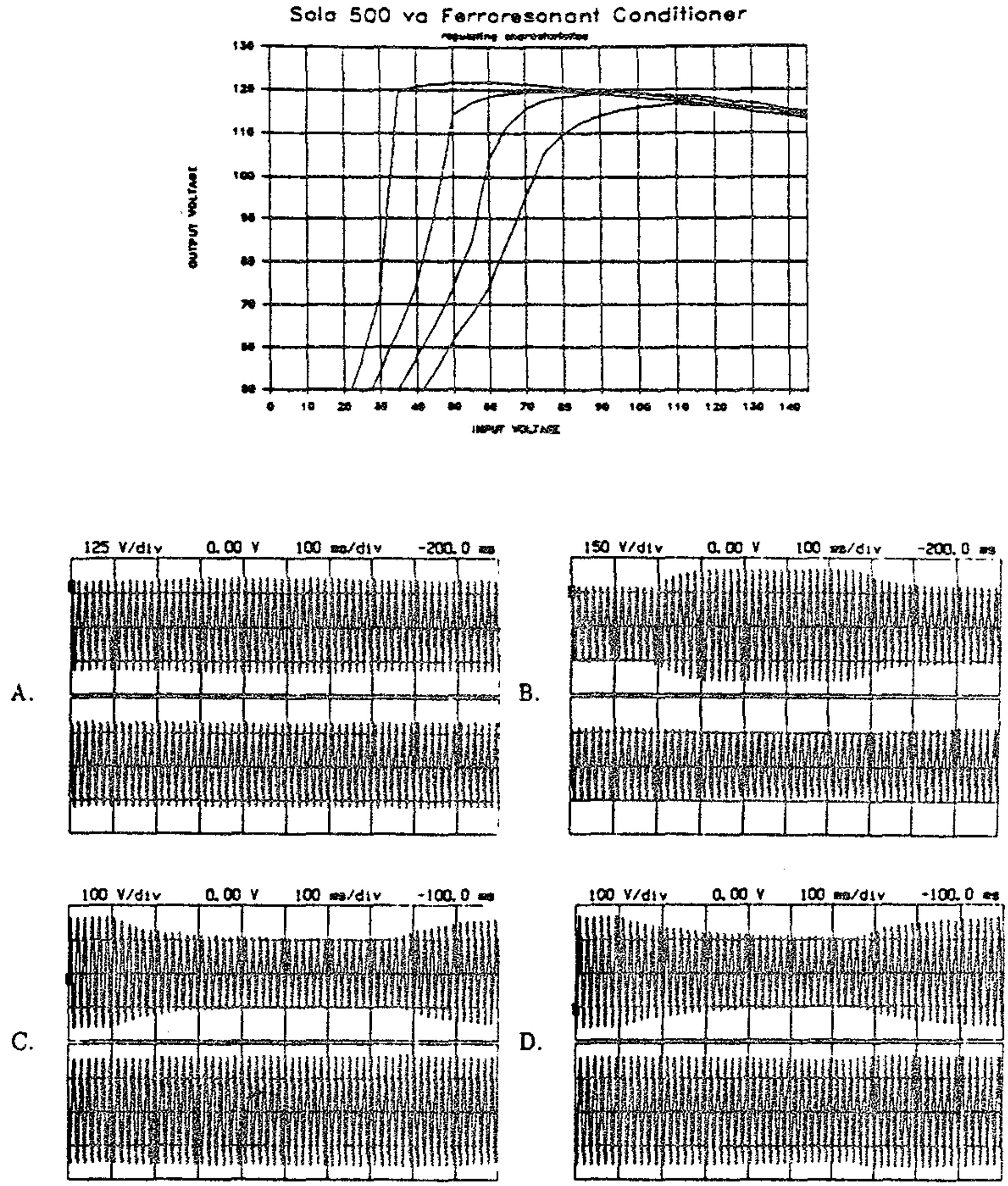
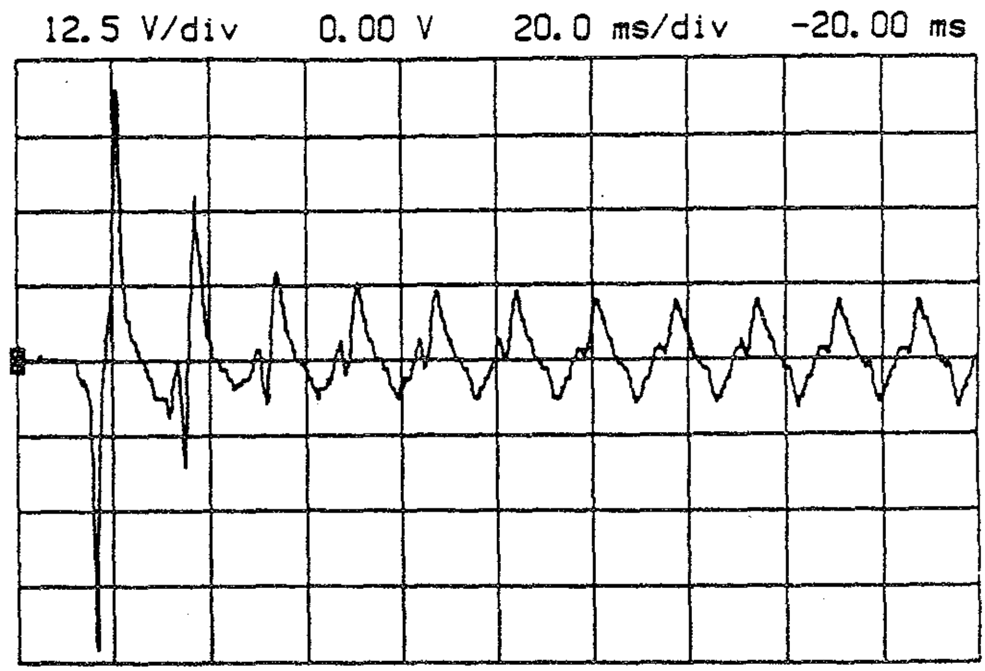


Figure D-9. Top: Sola 500 VA sinusoidal ferroresonant transformer output regulation characteristics. A) Output holds at 120 V_{rms} for a voltage surge to 130 V_{rms}. B) Output holds at 120 V_{rms} for a voltage surge to 150 V_{rms}. C) Output holds at 118 V_{rms} as input sags to 70 V_{rms} at 1/2 rated load. D) A sagging input voltage of $80V_{rms}$ under full load conditions begins to collapse output voltage.



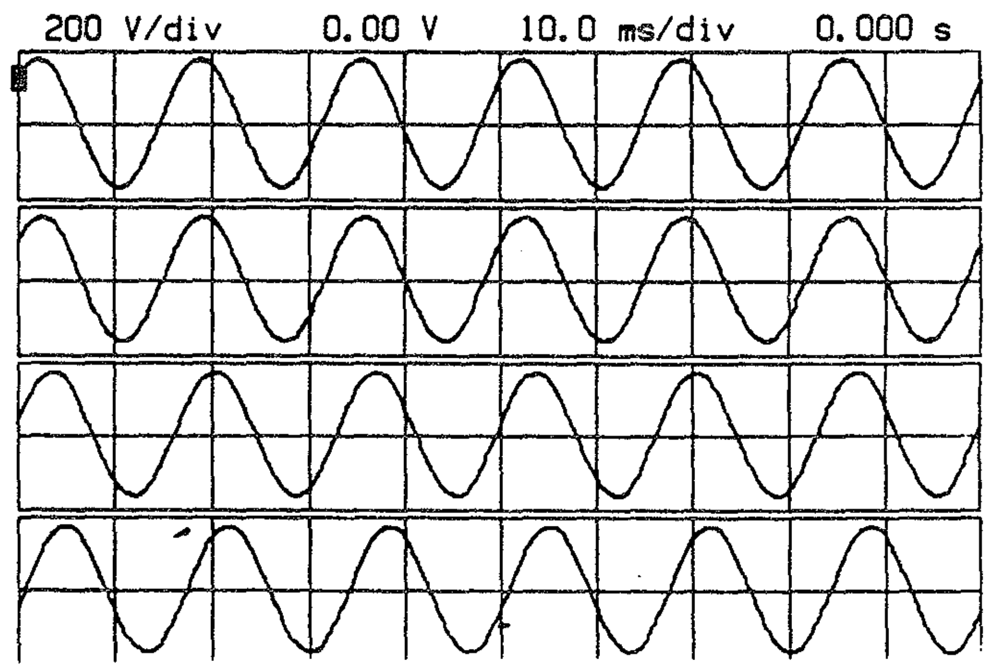
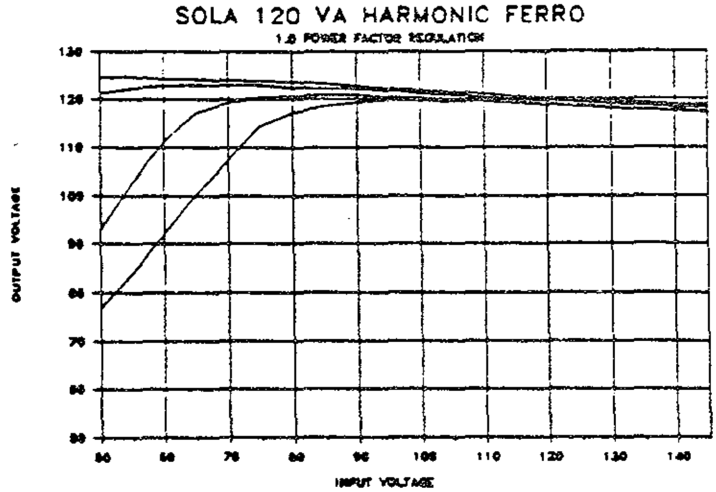
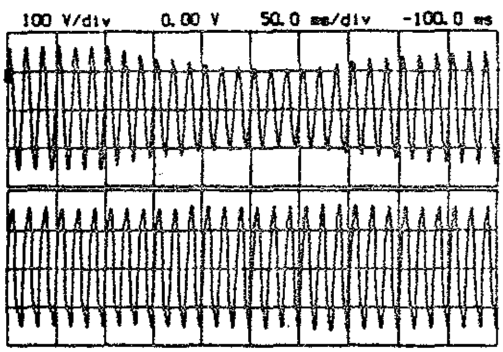


Fig. D-10. Top: Inrush current of the Sola 500 VA ferroresonant transformer. The first cycle peaks correspond to an instantaneous current of 20 amperes. Bottom: The Sola 500 VA ferroresonant transformer output waveforms under various resistive loading of 125 W, 250 W, 375 W and 500 W.



A.



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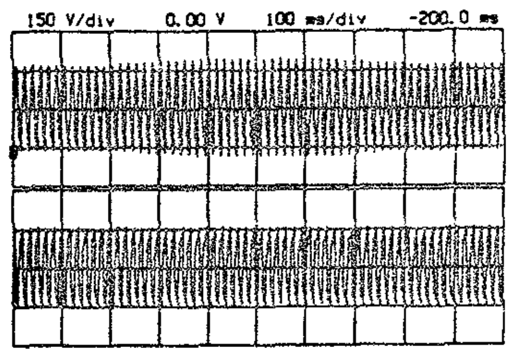

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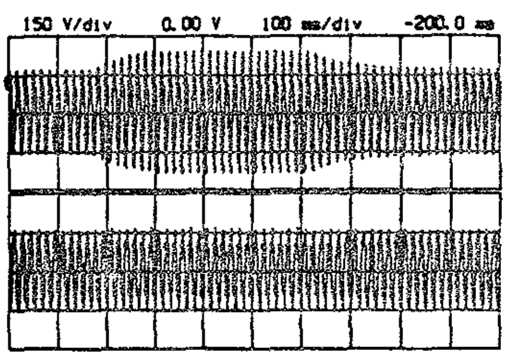


D.

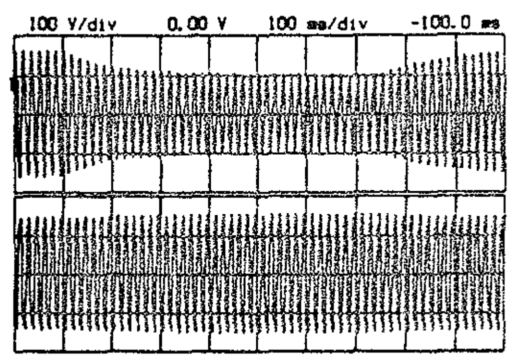
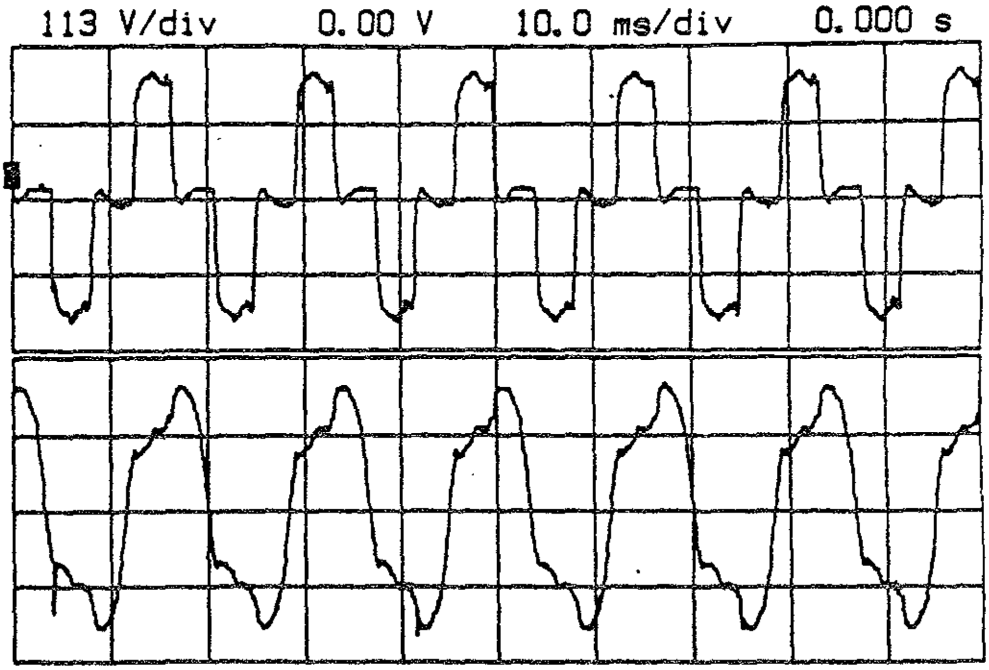


Figure D-11. Top: Sola 120 VA normal harmonic output ferroresonant transformer regulation characteristics. A) Output holds at 120 V_{rms} for an input voltage sag to 70 V_{rms} at 1/4 load. B) Output holds at 120 V_{rms} for a voltage surge to 140 V_{rms} at 1/2 load. C) Output holds at 120 V_{rms} as input surges to 170 V_{rms} at 3/4 rated load. D) A sagging input voltage of 70 V_{rms} is held at a nominal 120 volt output level at 1/2 load.



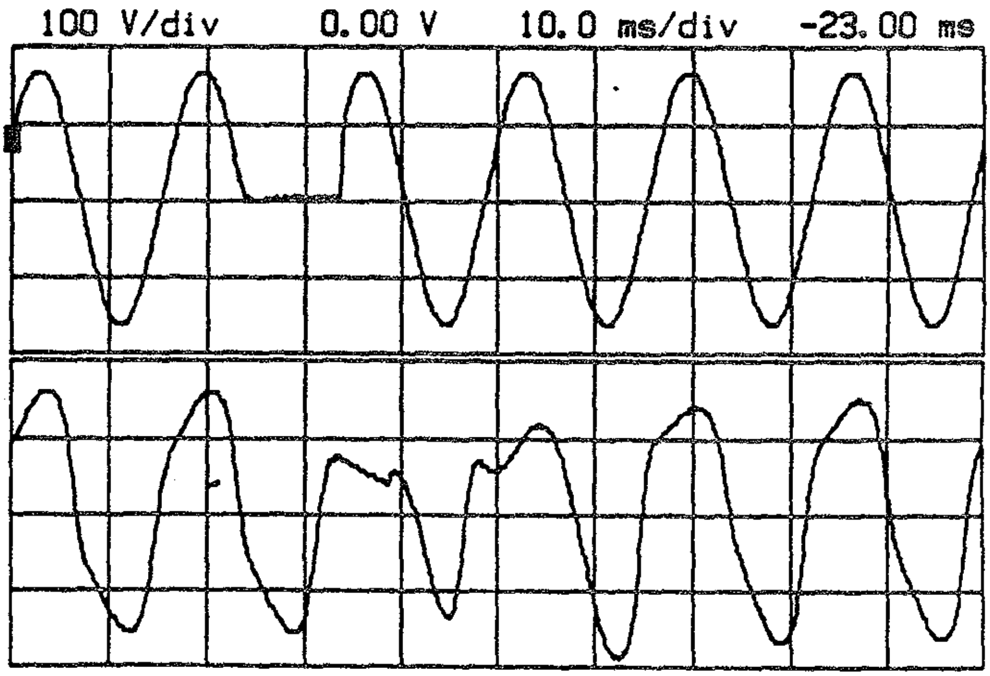


Fig. D-12. Top: A modified squarewave is used as the input to the Sola 120 VA harmonic ferroresonant transformer. The lower waveform represents the filtered transformer output at 1/2 load. Bottom: The Sola 120 VA ferroresonant transformer responds to the 1/2 cycle voltage dropout test under full load.

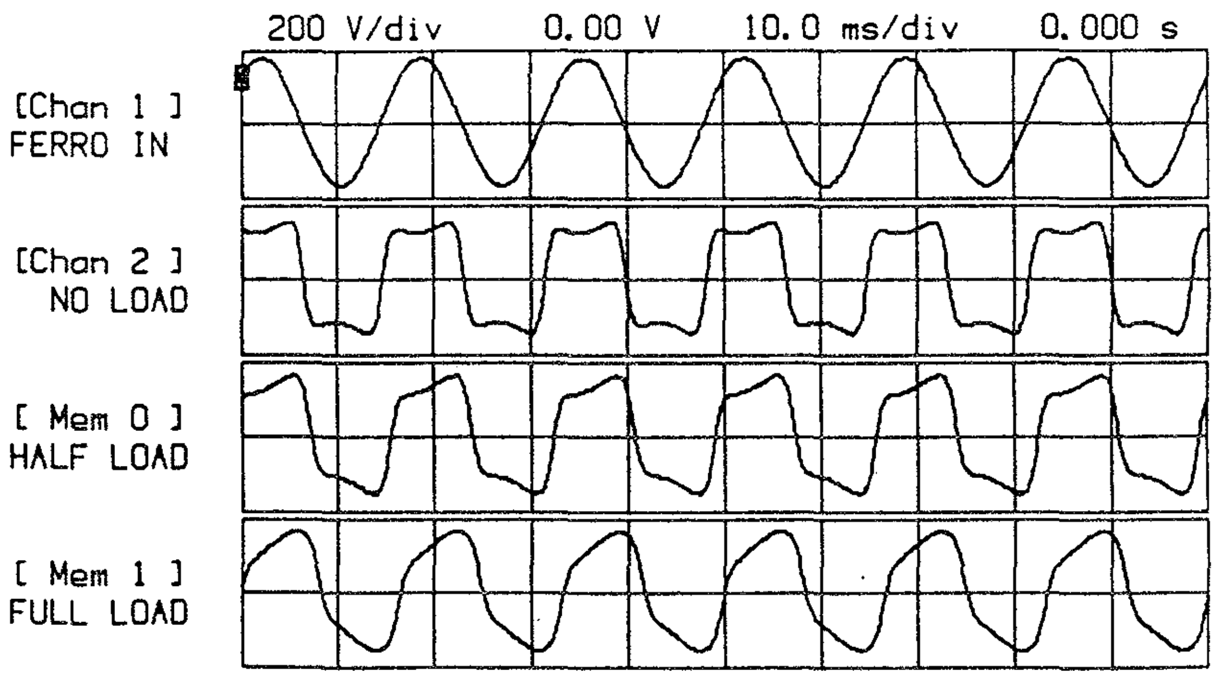


Fig. D-13. Output waveforms of the Sola 120 VA normal harmonic ferroresonant transformer under various resistive load levels. From top to bottom: Input 120 V_{rms} sinewave, 1/2 load output, 3/4 load output, full load output.

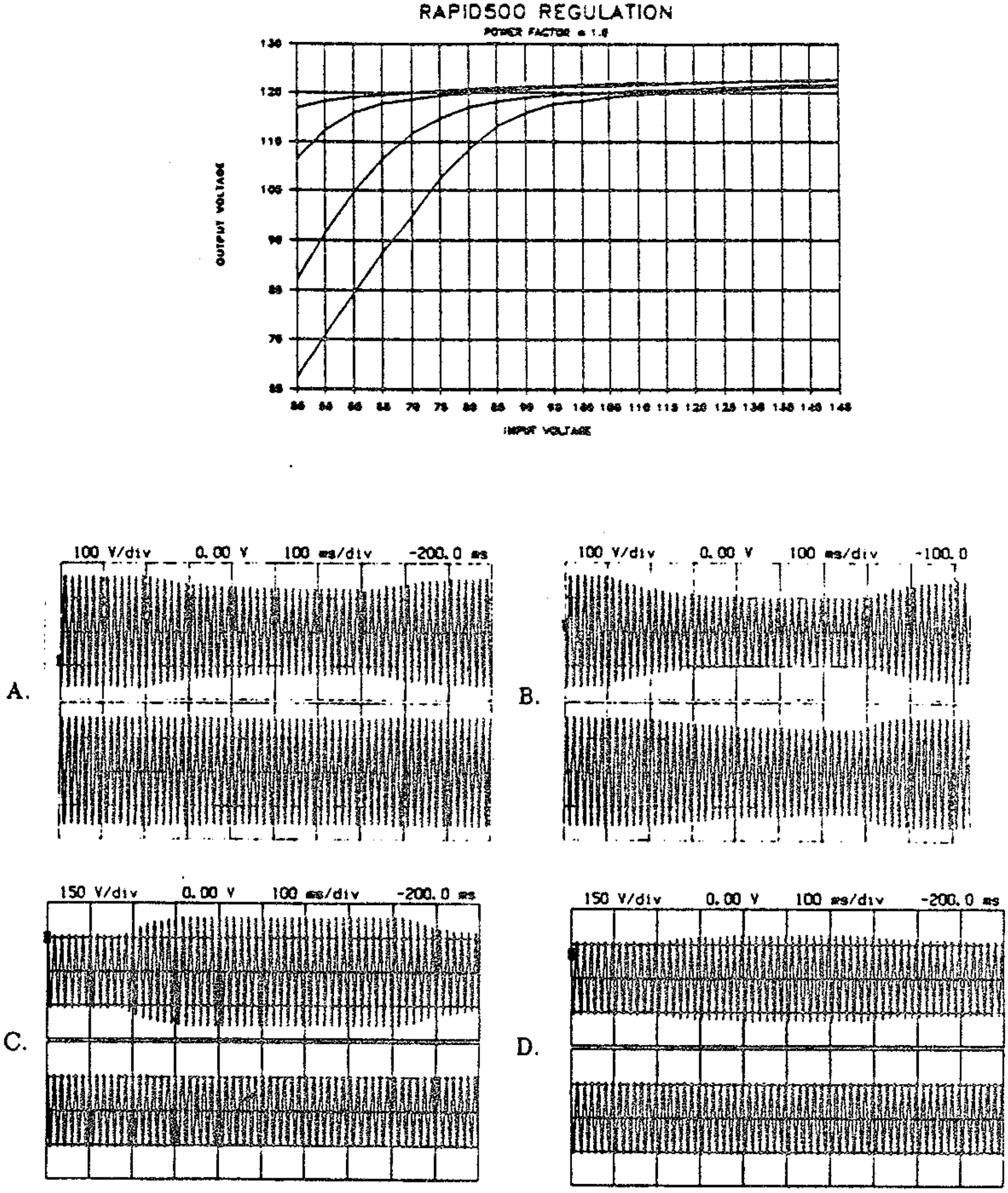


Figure D-14. Top: Rapid 500 VA ferroresonant transformer regulation characteristics. A) Output holds at 114 V_{rms} for an input voltage sag to 90 V_{rms} at full load. B) Output voltage falls to 90 V_{rms} for an input sag to 70 V_{rms} at full load. C) Output holds at 120 V_{rms} as input surges to 170 V_{rms} at full load. D) A surging input voltage of 140 V_{rms} is held at a nominal 120 volt output level at full load.

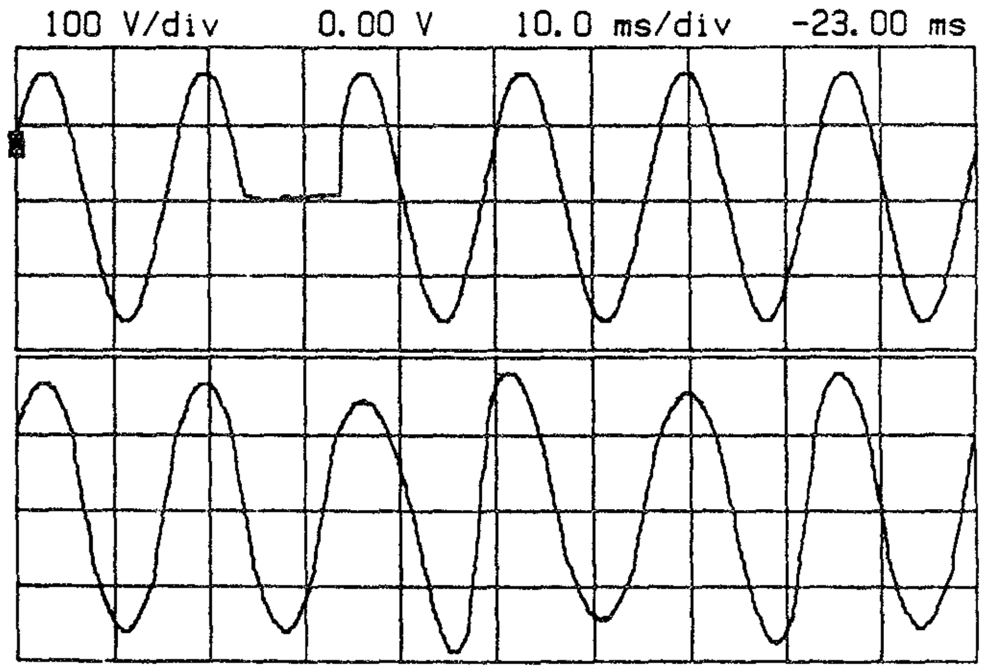


Figure D-15. The Rapid 500 VA ferroresonant transformer responds to the 1/2 cycle voltage drop test.

Appendix E

Comparison of Voltage Clamping Levels of Surge Suppressors, Power Conditioners, Isolation Transformers and Uninterruptible Power Systems to High-Magnitude Impulse Voltages

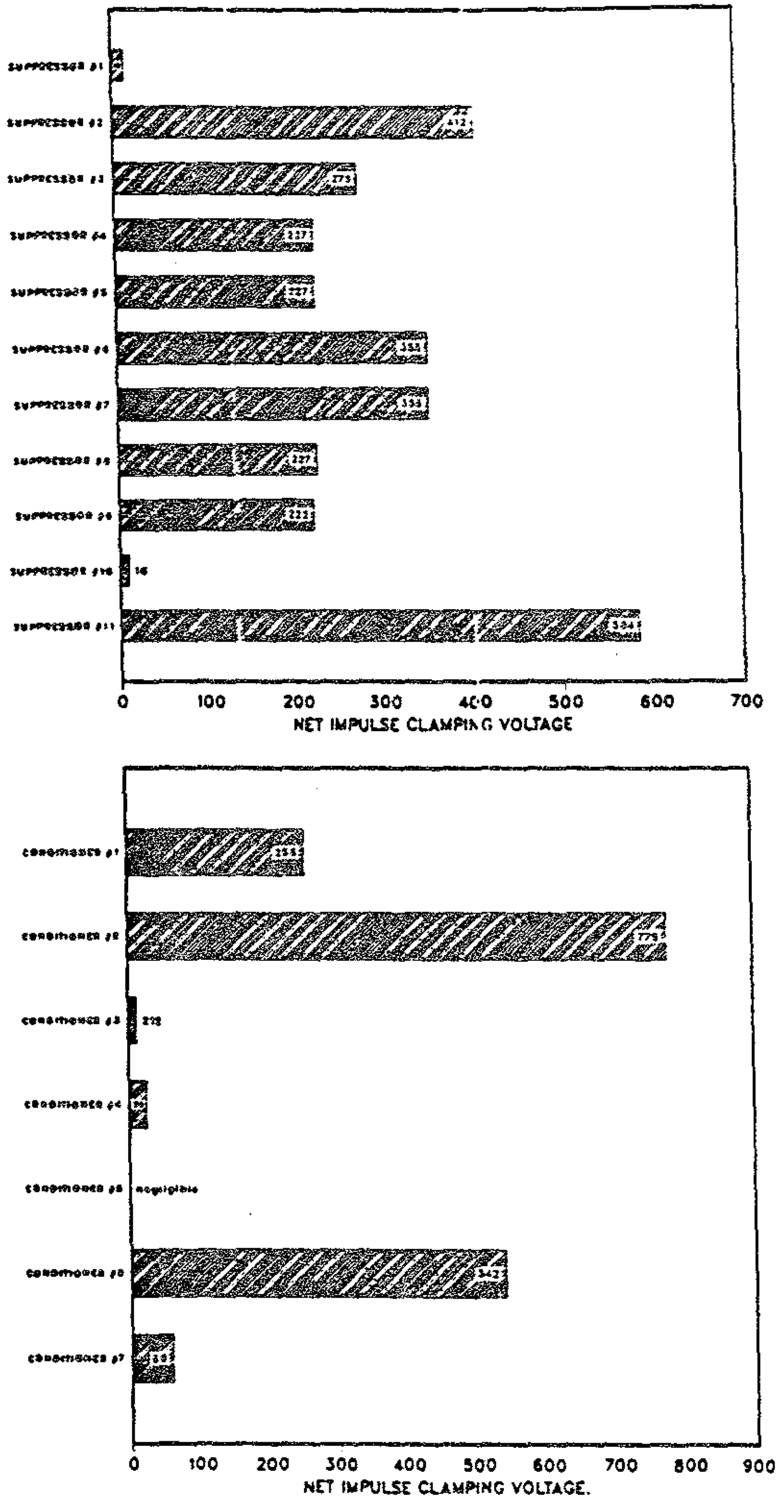


Fig. E-1. Line to neutral voltage clamping levels of surge suppressors (top) and power conditioners (bottom) to a 3.0 kV normal mode ringwave.

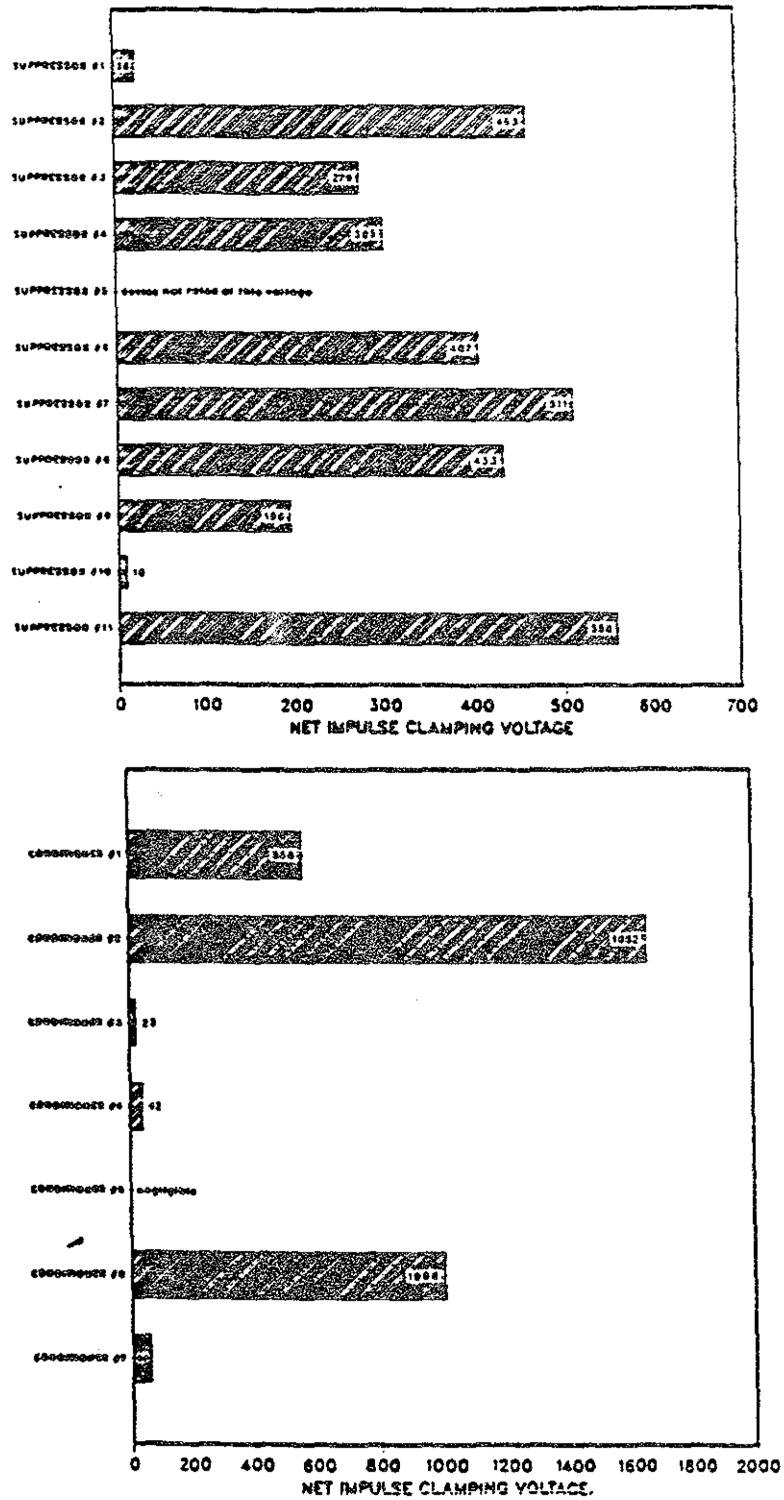


Fig. E-2. Line to neutral voltage clamping levels of surge suppressors (top) and power conditioners (bottom) to a 6.0 kV normal mode ringwave.

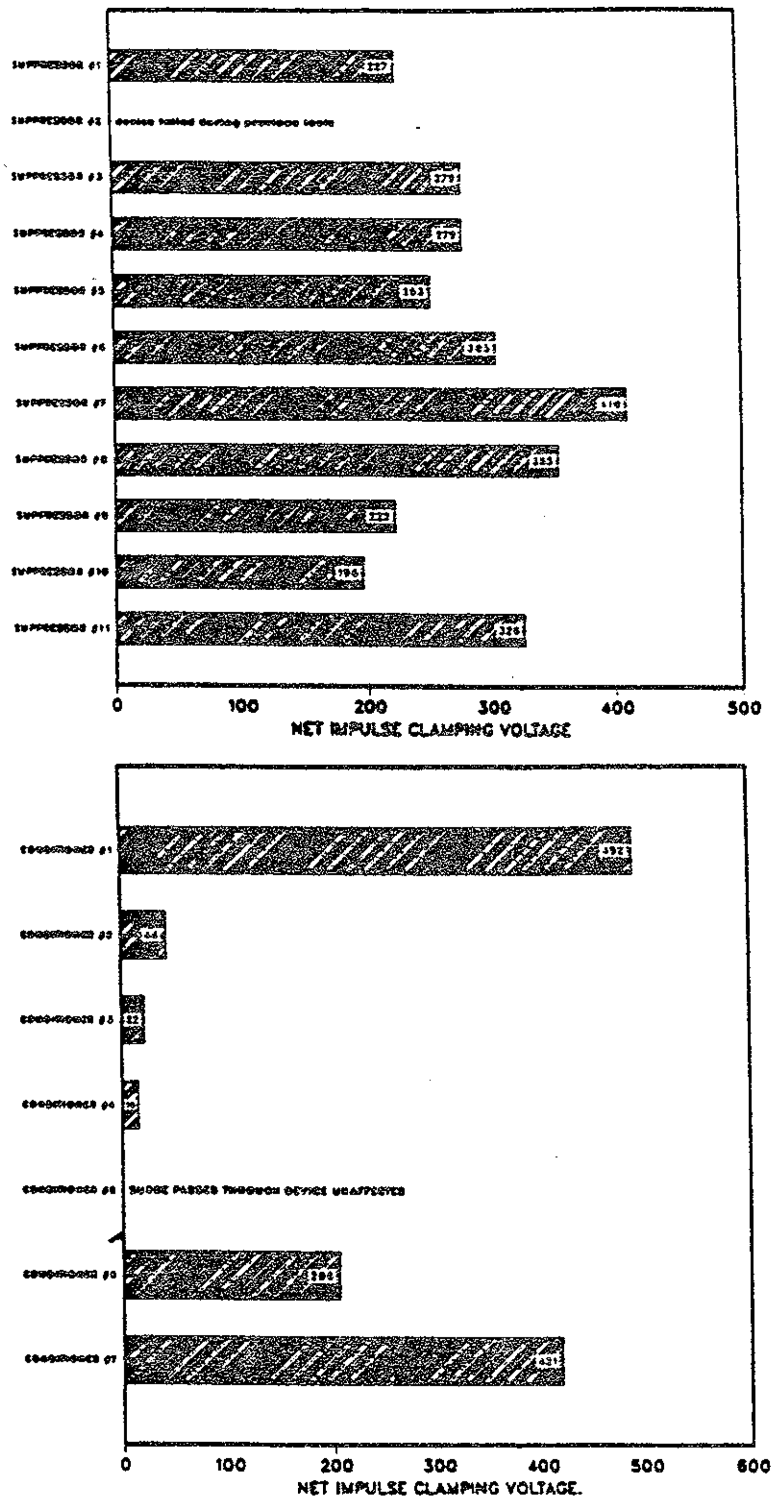


Fig. E-3. Line to ground voltage clamping levels of surge suppressors (top) and power conditioners (bottom) to a 3.0 kV common mode ringwave.

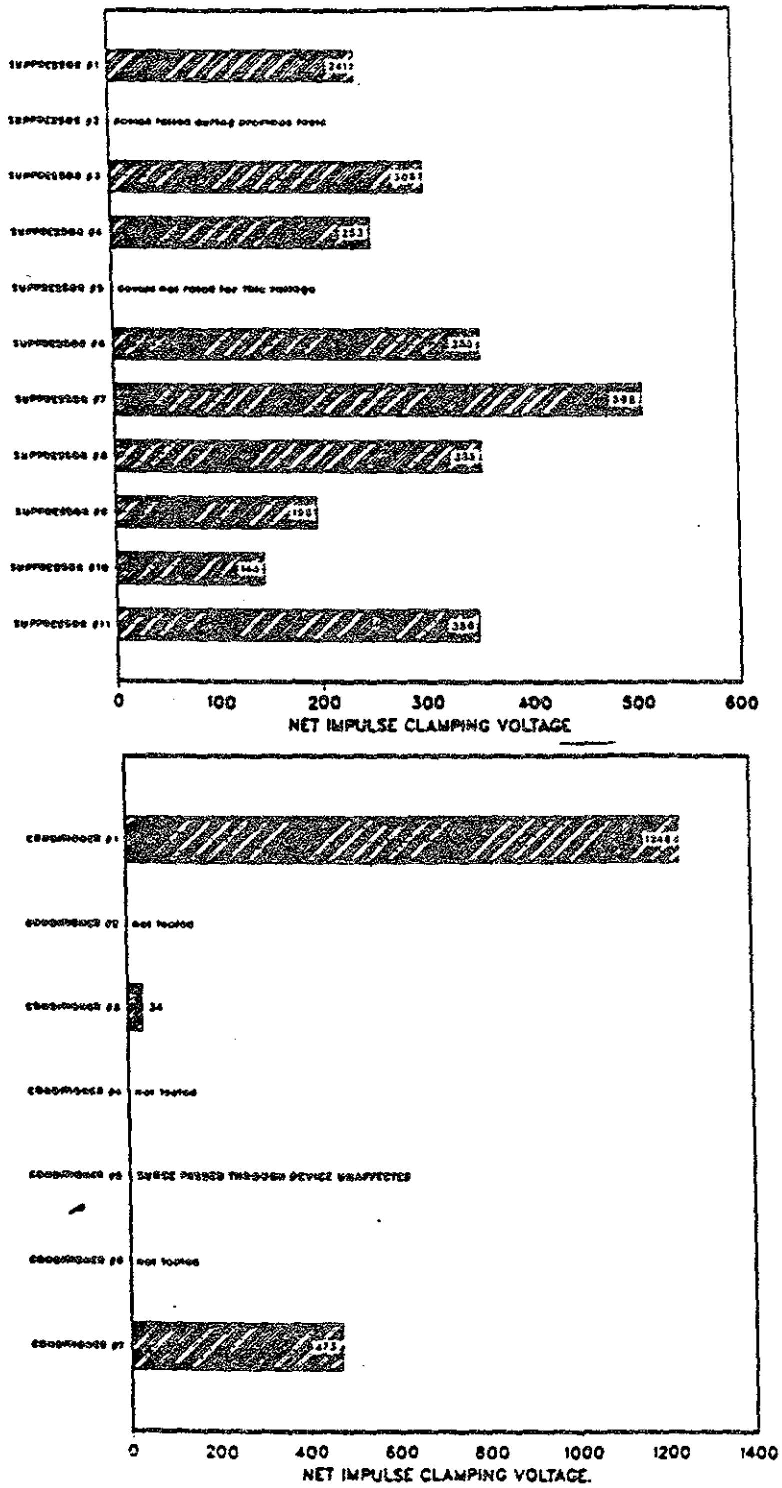


Fig. E-4. Line to ground voltage clamping levels of surge suppressors (top) and power conditioners (bottom) to a 6.0 kV common mode ringwave.

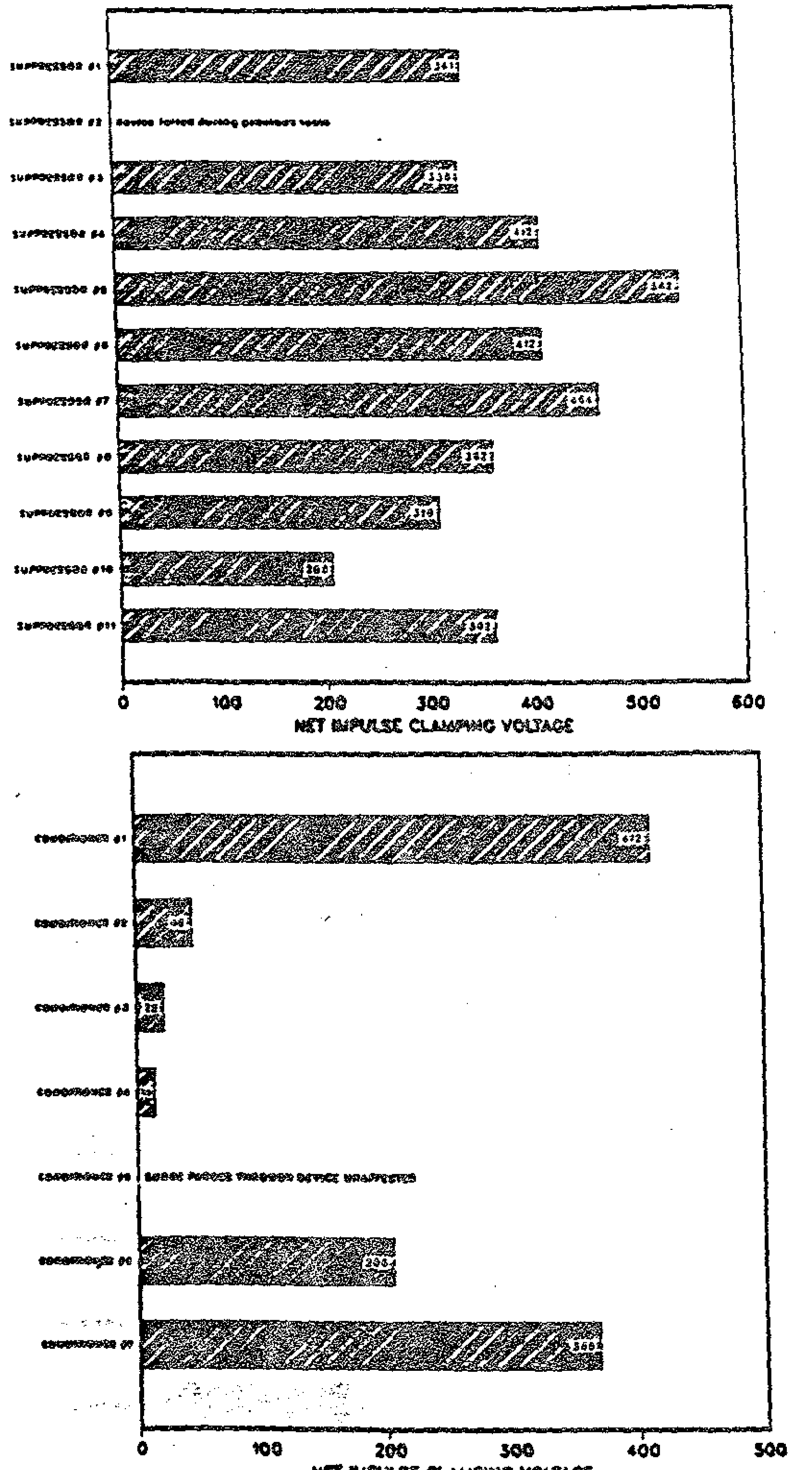
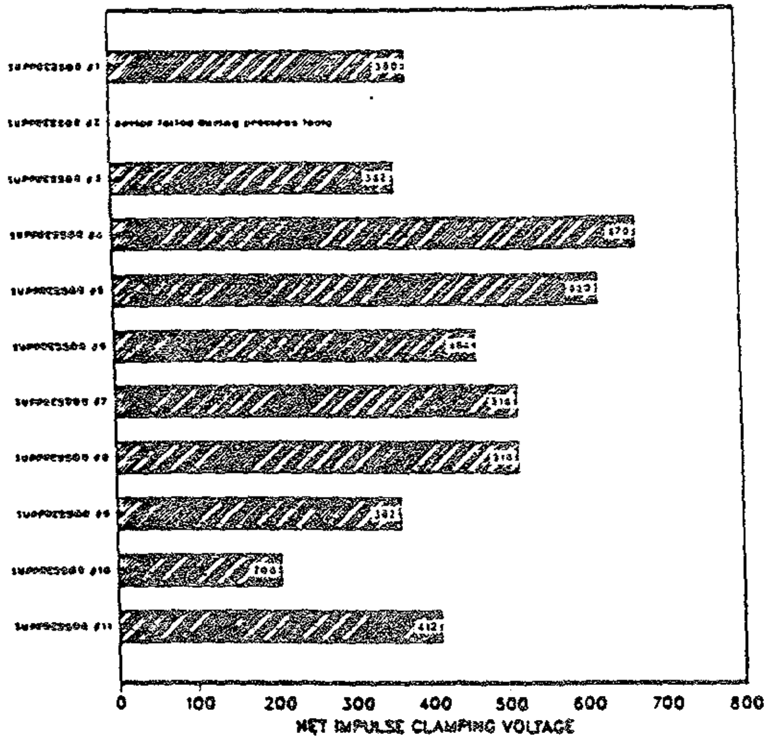


Fig. E-5. Neutral to ground voltage clamping levels of surge suppressors (top) and power conditioners (bottom) to a 3.0 kV common mode ringwave.



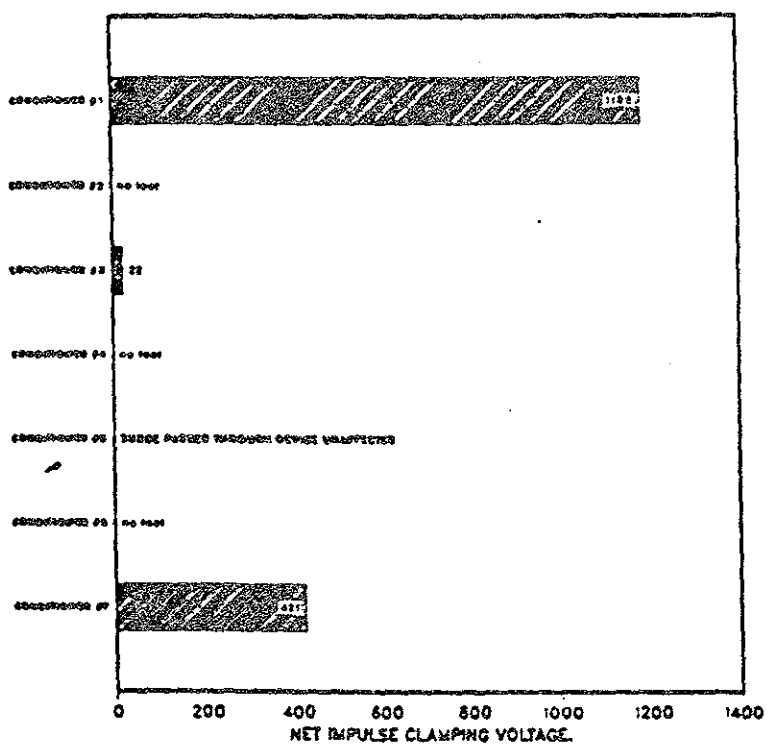


Fig. E-6. Neutral to ground voltage clamping levels of surge suppressors (top) and power conditioners (bottom) to a 6.0 kV common mode ringwave.

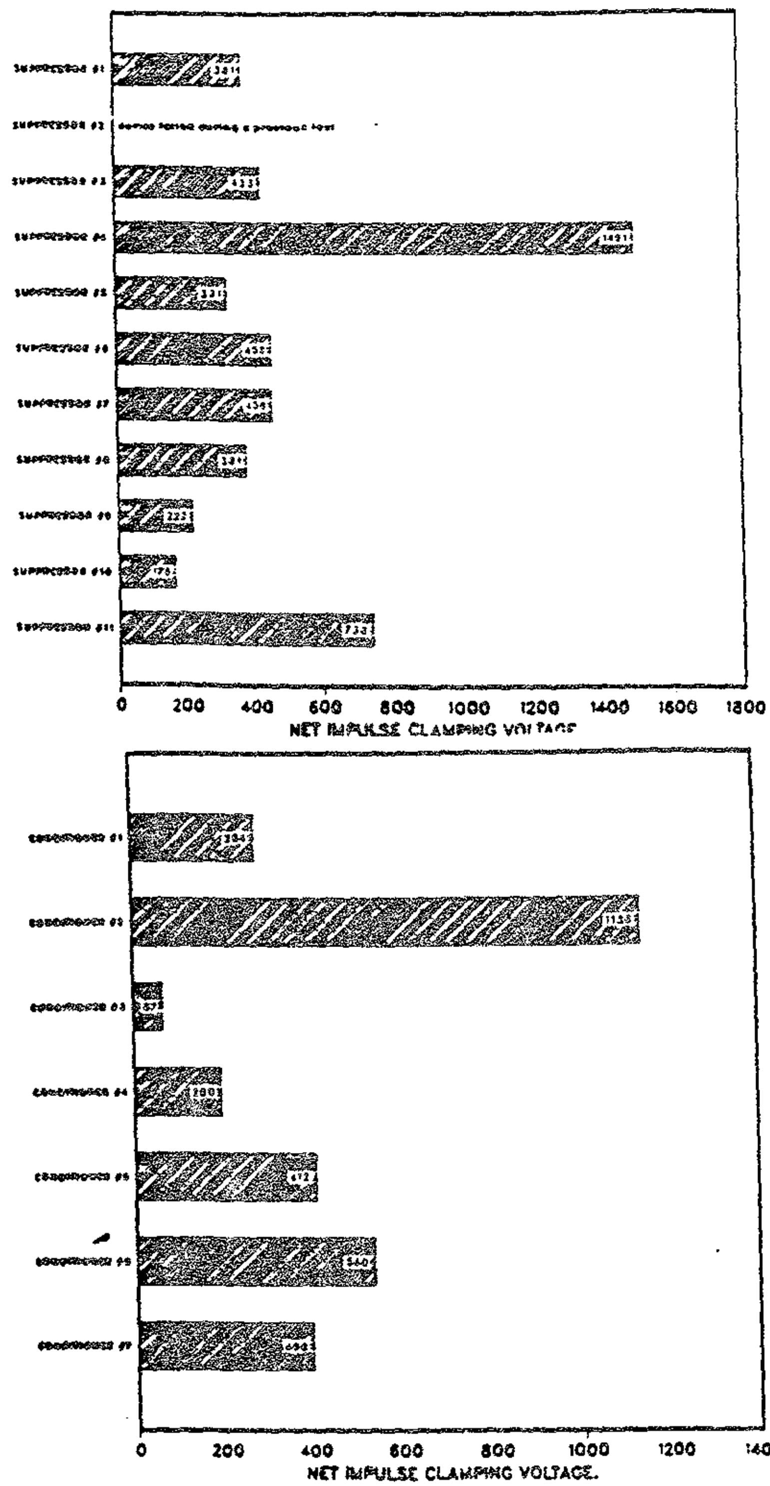
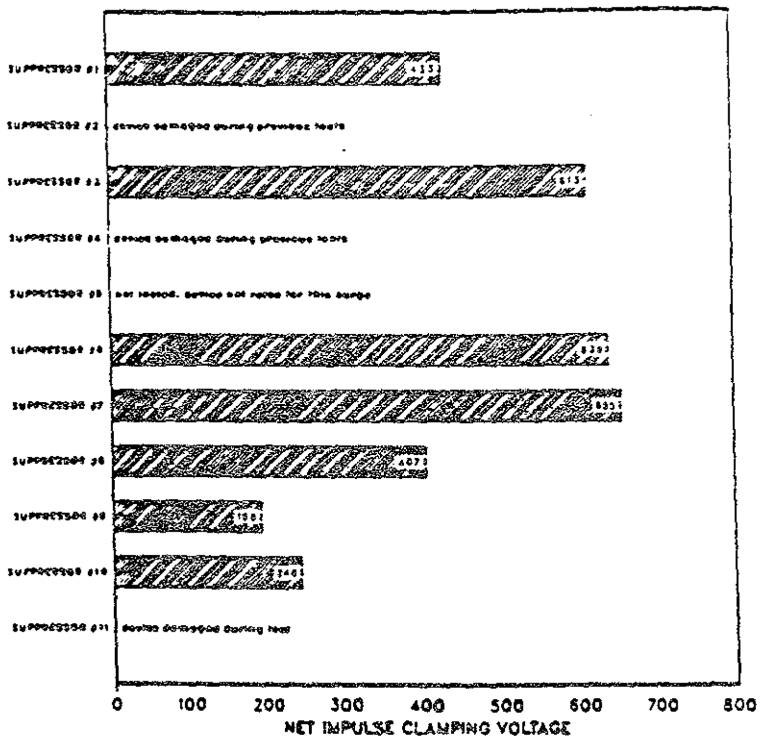


Fig. E-7. Line to neutral voltage clamping levels of surge suppressors (top) and power conditioners (bottom) to a 3.0 kV normal mode unipolar impulse.



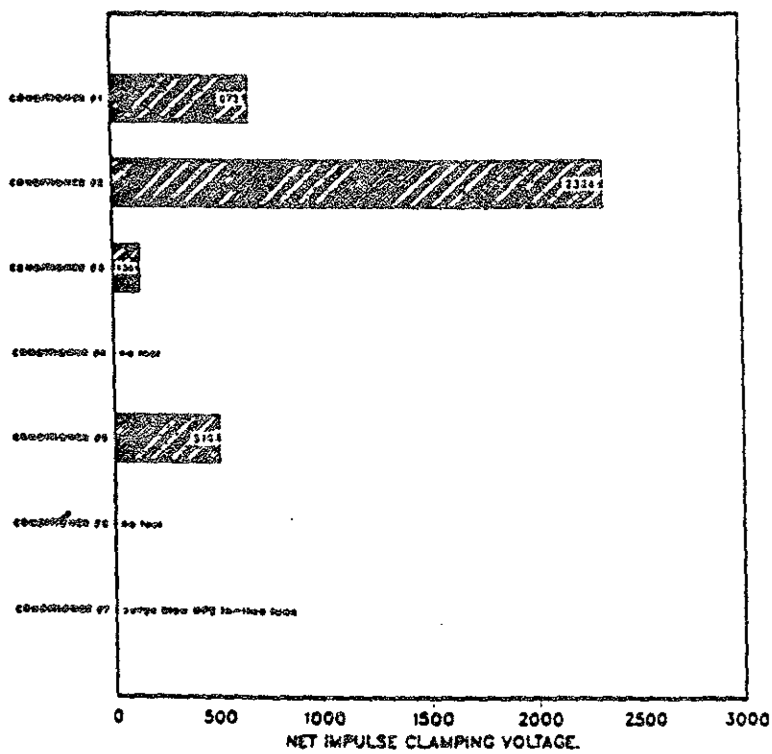


Fig. E-8. Line to neutral voltage clamping levels of surge suppressors (top) and power conditioners (bottom) to a 6.0 kV normal mode unipolar impulse.

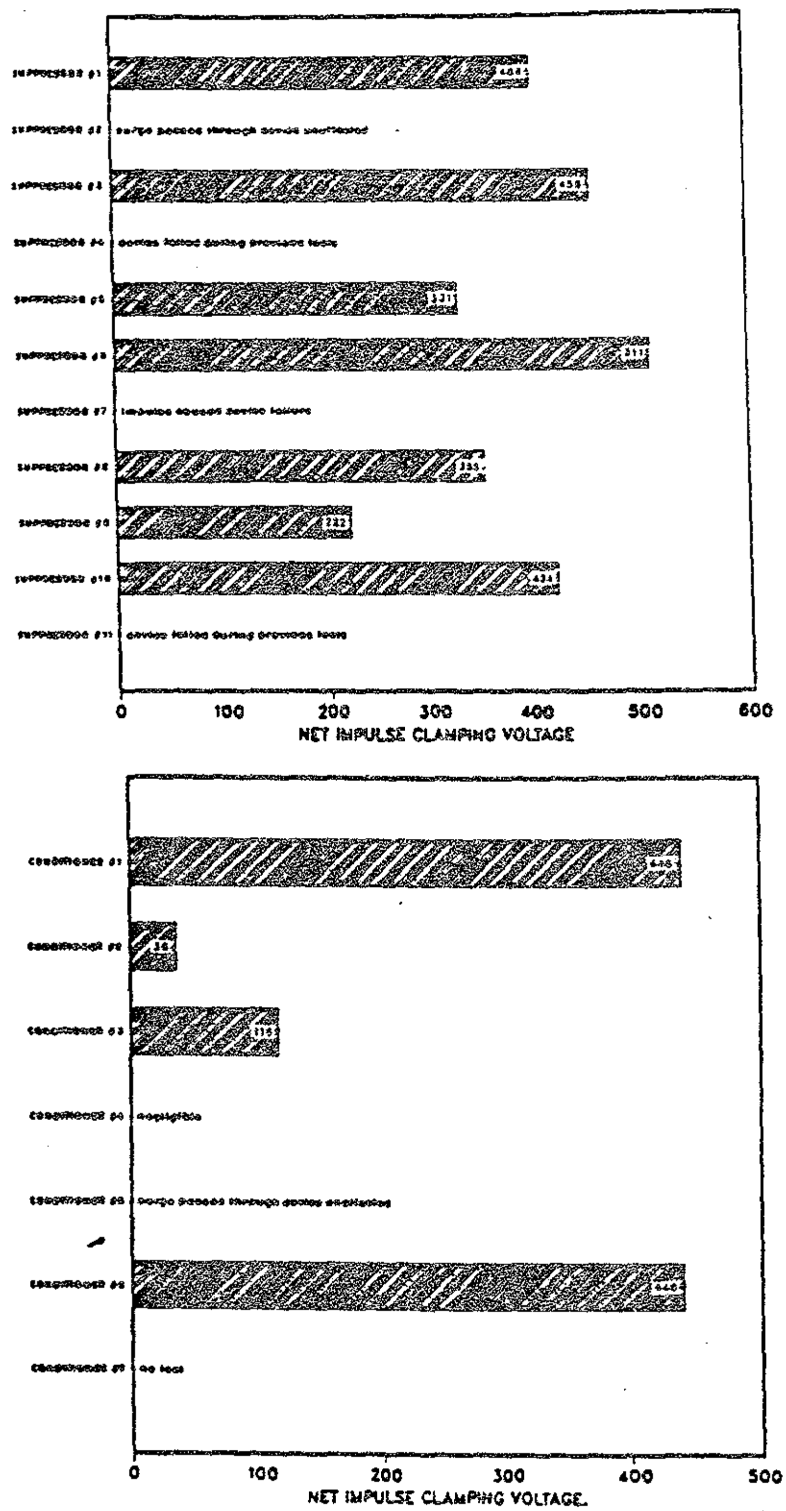
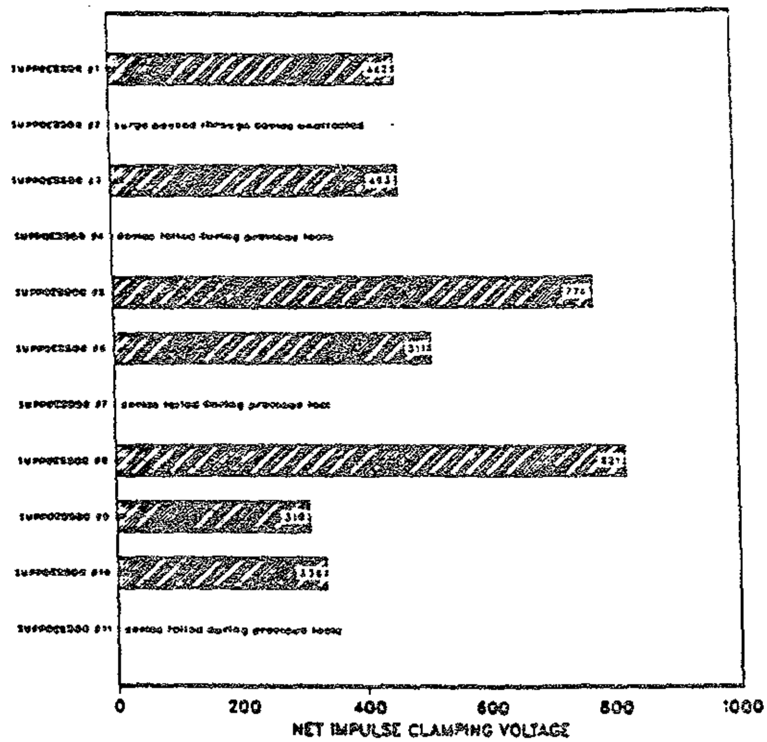


Fig. E-9. Line to ground voltage clamping levels of surge suppressors (top) and power conditioners (bottom) to a 3.0 kV common mode unipolar impulse.



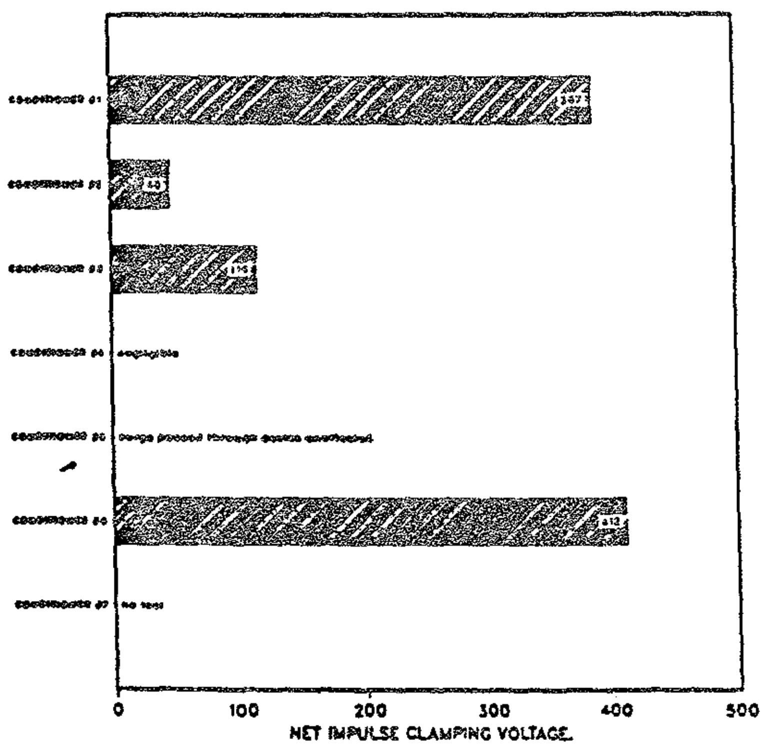


Fig. E-10. Neutral to ground voltage clamping levels of surge suppressors (top) and power conditioners (bottom) to a 3.0 kV common mode unipolar impulse.

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